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Cropping Pattern Optimization in the Context of Climate-Smart Agriculture: A Case Study for Doroodzan Irrigation Network- Iran

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Abstract

Modern irrigation systems are considered as a way to both respond to the effects of climate changes and improve the water security. Applying such systems, save the water used in farming activities and consequently made some environmental challenges in terms of increasing energy consumption and greenhouse gas emissions. Although some recent studies analyzed the relationship between water and energy in the agricultural irrigation systems, considering the objectives on productivity, adaptation, and mitigation in a cropping pattern optimization problem is necessary. Climate-Smart agriculture as a strong programming concept, addresses these three objectives and has created the potential for a "triple-win" solution. This study is an effort to fill the study gap on triple-win solution in modern irrigation by developing an integrated economic-hydrological-environmental model called WECSAM at the basin level using a hydrological model called WEAP. For this purpose, a multi-objective optimization model has been developed with the concepts of water footprint, energy footprint, and the greenhouse gas emissions in the context of CSA. We applied the model to the northern region of Bakhtegan basin called Doroodzan irrigation network located in Iran. The result of the WECSAM model indicated that by simultaneously optimizing the conflicting objectives of maximizing profit and minimizing water footprint, energy footprint, and CO_2 emissions, as compared to the single-objective model of maximizing economic profit, the water footprint decreases by 8.2%, Energy footprint decreases by 21.2%, CO_2 emissions decreases by 6.9% and profit decreases by 7.4%. The share of each system in irrigating the water-smart, energy-smart, and climate-smart cropping pattern is as follow: 54% for drip system, 26% for semi-permanent sprinkler system, 11% for surface systems, 8% for center-pivot, and <1% for classic permanent sprinkler system.

Keywords: Cropping Pattern, Climate-Smart Agriculture, CO_2 Emission, Irrigation Systems, Multi-objective Optimization, Water Footprint

Introduction

Increasing world population and consequently expanding demand for agricultural crops associated with the pressure on water resources caused by climate change, has made a major challenge for agriculture to ensure food security of communities (Escriva-Bou *et al*., 2018; Wang *et al*, 2017; Galan-Martin *et al*., 2017). In recent decades, one of the main adaptation strategies to respond to food security challenge is the development of irrigated agriculture and improving the water use efficiency (García *et al*., 2014; Tarjuelo *et al*., 2015; Hardy *et al*., 2012; Daccache *et al*., 2014; Schwabe *et al*., 2017; Hanjra & Qureshi, 2010). Irrigation cultivation area worldwide has increased from 161,148,000 ha in 1961 to 338,710,000 ha in 2018. More than 70% of the surface and groundwater are have been applied for the agricultural application (Dehghanipour *et*

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al., 2020) while 90% of this amount is consumed in arid and semi-arid regions (Tarjuelo *et al*., 2015; Molden, 2013). Development of modern irrigation infrastructure and pressurized irrigation systems, as a strategy to improve both water and food security through increasing crop yield and reducing irrigation water use, plays a substantial role in intensifying the production of agricultural crops in arid and semi-arid areas (Fouial *et al*., 2016).

The modern irrigation technologies are considered as a way to manage the effects of climate change as well as to improve the water security. Nevertheless, although some modern irrigation technologies may save the water consumption volume (Playán & Mateos, 2006), employing such systems as a single strategy to respond to rising food demand contains a serious challenge in terms of increasing Energy consumption as well as greenhouse gas (GHG) emissions, and even economic challenges (Mushtaq *et al*., 2013; Schwabe *et al*., 2017). so recently, many researchers has been paid attention to study the performance of these systems (Rodríguez-Díaz *et al*., 2007; Fernández García *et al*., 2014; Daccache *et al*., 2014; Hardy and Garrido, 2012; Levidow *et al*., 2014; Mushtaq *et al*., 2013; Rodríguez-Díaz *et al*., 2012; Carrillo Cobo *et al*., 2014; Zhao *et al*., 2020; Tarjuelo *et al*., 2015; Mateos *et al*., 2018; Espinosa-Tasón *et al.*, 2020). In this matter, world statistics indicate that about 23-48% of the world's agricultural energy is directly consumed by the irrigation pumps (Mushtaq *et al*., 2013; Zhao *et al*., 2020). A study conducted by Fernández García *et al*. (2014) revealed that with the development of modern irrigation systems, the water consumption has decreased by 23%, while the water costs have increased by 52%, mainly due to higher energy requirements. Espinosa-Tason *et al*. (2020), by creating “energized-water” term, showed that the conversion of the furrow irrigation system to drip and sprinkler irrigation systems in Spain, generated 600% increase in the energy consumption, tripled the cultivation area in the 1950–2017 period, and also doubled the water consumption for some periods. They indicated the importance of paying attention to choosing the irrigation methods in the management of agricultural systems.

Although some recent studies provided valuable analyses of the relationship between water and energy in the agricultural irrigation systems, and also highlighted the importance of extending these studies in water-scarce areas, but a significant number of them have resulted that there are some gaps in this field that required to be supplemented with more efforts. In this regard, Rodríguez Díaz *et al*. (2011) by developing a water and energy consumption assessment method in the pressurized irrigation networks in 10 sub-basins of representative Andalusian, concluded that there is a high requirement for energy to implement these irrigation systems. Accordingly, they suggested that water and energy should be optimized simultaneously. Mushtaq *et al*. (2013) using an integrated economic-environmental model, surveyed the trade-off between water storage, energy consumption, greenhouse gas emissions, and economic benefits in sprinkler, drip and surface irrigation systems. By emphasizing the complexity of exploring the effectiveness of modern irrigation systems to achieve the irrigation efficiency on farms, they showed that in order to optimize investment in new irrigation technologies, items that should be considered simultaneously in the crop system are adaptation, and mitigation measures. In this way it’s possible to achieve the most economic benefits, manage the effects of climate change, and also minimize negative effects on the environment.

Thus, to deal with the existing challenges, three factors of productivity, adaptation, and mitigation should be synthesized in management of agricultural systems. The concept of climate-smart agriculture (CSA) as a strong programming concept has been able to solve these three objectives simultaneously, which has created the potential for a "triple-win" solution (Long *et al*., 2016; Neufeldt *et al*., 2013). Here, the CSA is resistant to the climate change by improving productivity, sustaining farm incomes, increasing the water use productivity, and reducing the GHGs emissions. Water-smart, energy-smart, carbon-smart and knowledge-smart technologies can significantly, directly or indirectly, improve productivity, increase flexibility, and decrease the GHGs (Imran *et al*., 2019). It should be noted that **CSA** contains a wide range of technologies and practices, in which water and energy management are the most important (Palombi & Sessa, 2013; Olayide *et al*., 2016; Streimikis *et al*., 2020; Bogdanski, 2012). Nonetheless, having in mind the location-specific property of CSA (Palombi & Sessa, 2013), the technologies and practices employing in each region should be investigated to confirm its accordance with the CSA objectives.

In recent years, irrigation of many crops has been shifted towards modern irrigation systems and the level of irrigated cultivation area has increased in types of:

Classical permanent sprinkler irrigation system;

Semi-portable sprinkler irrigation system;

Center-pivot irrigation system;

Drip irrigation system.

Supporting farmer's livelihood, and, simultaneously, decreasing in river inflow as well as available water shrinkage, highlighted the importance of the integrated agricultural management.

It can be clearly concluded that regardless of the technical factors, the selection of irrigation systems in a region can meet the objectives of adaptation, mitigation, and productivity simultaneously only if its optimization take place alongside with cropping pattern in the context of CSA objectives. Although the importance of this problem has been highlighted in many studies, but in our knowledge, no study by now has presented the problem to optimize the cropping pattern and irrigation system based on CSA objectives. This study is looking to fill the study gap by developing an integrated economic-hydrological-environmental model at the basin level using a hydrological model called WEAP[1], which is a multi-objective optimization model synthesizied with the concepts of water footprint, energy footprint, and the GHGs emissions in the context of CSA. We are trying to answer questions on the necessity of converting to modern irrigation systems for all crops in order to achieve the objectives of CSA and what combination of crops and irrigation systems can be acceptable to obtain a smart farming system.

Methodology

The water supply challenges, by maximizing the farmers' profits while ensuring the sustainability of the natural ecosystem, require the use of multi-objective optimization models (Giupponi, 2007). In this study, in order to meet the objectives of CSA to determine the optimal cropping pattern and irrigation systems, these following objectives are considered:

- Maximizing economic profit

  Minimizing water footprint

  Minimizing energy consumption

  Minimizing CO_2 emissions

One of the most important parts of these components is the water resource available in the basin, which should be allocated among urban, industry and agriculture sectors using different policy priorities and also between different crops. In some studies, fuzzy methods have been applied to deal with this uncertainty (Li *et al*., 2019; Mardani Najafabadi *et al*, 2019). However, in some other studies, it is suggested that basin simulation models can be applied to facilitate decisions related to complex irrigation systems that depend on various variables, parameters, processes, and uncertainties (Escriva -Bou, 2018; Mirzaei & Zibaei, 2020). In this study, we utilized the WEAP-MABIA model to determine the amount of available water as well as simulating the yield and water requirements of crops in the study area. Likewise, by calculating the effective evapotranspiration by WEAP, the water footprint index was considered instead of the usual physical requirement. Compared to physical water, the water footprint is a more useful tool to achieve cleaner production in real-world agricultural water management practices (Dai *et al*., 2021). A complete description of the general framework of the model, the WEAP-MABIA model, multi-objective mathematical model for obtaining water and energy footprints, and CO_2 emissions are described in the following sections.

Integrated Model Context

The general framework of the model is provided in Fig. 2. In the first step, by entering the climate data, land use, soil, water resources, plant information, irrigation, and agricultural, city, industry, and environmental demand sites and their approved priorities in the region, finally calibrating the WEAP model, we were able to simulate the actual measures of water resources, water requirement, and crop yield. Besides, with the use of effective evapotranspiration, and reference transpiration obtained from the WEAP model, the water footprint index of the selected crops is calculated in the region. The energy footprint per hectare has been calculated for different irrigation crops and systems by using information on the irrigation systems and energy, water consumption, and crops yield. Meanwhile, using the emission data described in the section data, the emission amount of each crop was assessed in different irrigation systems. After these calculations, a multi-objective hydrologic-economic-environmental model was set. By solving the multi-objective model using the genetic algorithm (GA) method, we obtained the Pareto frontier function. Then, by giving the same weights to our

1- Water Evaluation And Planning System (WEAP) four objectives in TOPSIS method, the most effective crop pattern irrigated with the best combinations of irrigation systems was chosen as well.

Water Evaluation and Planning System (WEAP)

The Water Evaluation and Planning System (WEAP) is a useful and practical tool for the comprehensive water management (Esteve *et al*., 2015; Blanco-Gutiérrez *et al*., 2013), which was developed by the Stockholm Environment Institute (SEI). WEAP, in addition to being a tool for forecasting and policy analysis, by considering the supply and demand sides of water resources, can provide a comprehensive delineation of the current state of water supply resources as well as demand side of the basin (Yates *et al*., 2005). By employing the MABIA method in WEAP, the processes of evapotranspiration, runoff**,** infiltration, and irrigation requirements at the basin can be simulated. The MABIA method is a daily simulation of evapotranspiration, irrigation and planed requirements, crop growth and yield, which includes some modules to estimate reference evapotranspiration and soil water capacity (Jabloun & Sahli, 2012).

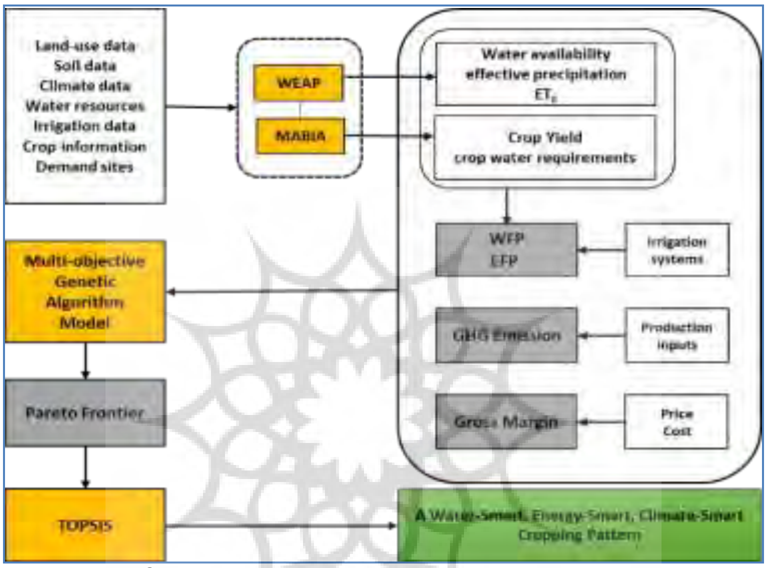


Fig. 1- Framework of the Water-Energy-Climate Smart Agriculture Model (WECSAM)

Table 1- Cropping pattern of the study area

Catchment	Area (ha)	Crop pattern
Main & Abarj	9317	Wheat (67.5%), Barley (1.8%), Tomato (6.7%), Rice (17.2%), Corn (3.1%)
Left side	14481	Wheat (64.6%), Barley (3.9%), Tomato (6.7%), Rice (2.6%), Corn (20.6%)
Ordibehesht	6015	Wheat (76.2%), Barley (4.2%), Tomato (2.4%), Rice (1.6%), Corn (9.3%)
Hamoon	16078	Wheat (74.6%), Barley (18.2%), Rice (1.1%), Corn (1.1%)
Continue of the left	7714	Wheat (64.2%), Barley (17.4%), Tomato (1.9), Corn (7.3%)
Continue of the right	3240	Wheat (88.9%), Barley (11.1%)
Total	56845	Wheat (70.5%), Barley (90%), Tomato (3.3%), Rice (4.0%), Corn (8.0%), Others (4.3%)

In order to simulate evapotranspiration, effective rainfall, water requirements of crops, yield, and water available for agriculture in this study, city demand node with priority 1, industrial demand node with priority 2, and agricultural catchments and the environmental demand of Bakhtegan wetland with priority 3 were defined. Since Doroodzan irrigation network is divided into 6 regions, 6 agricultural catchments are defined so that available water resources and cultivation areas and other information can be carefully entered into the model. However, as the decisions are made for the multi-objective model at the level of the irrigation network, the whole area has been aggregated. Information on the cultivated areas are reported in Table 1.

The model was calibrated by comparing the observed and simulated values of variables like river flow, yield and water requirement. Plant parameter including basal crop coefficient were used for calibration, and the values of calibrated water need and yield is presented in Table 2. Model accuracy is measured using the standardized bias score that showed a good level of accuracy with a bias of less than 20% (see Esteve *et al*. (2015)).

Table 2- WEAP calibration parameters

Parameter	Barley	Forage crop	Rice	Tomato	Wheat
'basal' crop coefficient, K_{cb}*	0.50	0.67	0.92	0.68	0.55
Net water requirement** (m^3)	2759.93	3113.49	11333.55	8889.42	3332.16
Yield (tons)	2.88	58.44	5.35	67.72	4.55

*Average of three stages of plant growth
** Weighted average of irrigated catchments

then were included in the proposed model. In the following, the objectives and constraints of the model are described and also the definition of the symbols used in the model are available in table 3.

The profit of the agricultural system. The most important criterion that many decision makers consider to choose the cropping pattern at different scales from a farm to region, is the profit obtained from the agricultural activity, which reflects both economic development (at regional scale) and farmers' livelihoods and income (on a farm scale) (Li *et al*., 2019). The profit function is explained using Eq. (1).

$$Profit^{max} = \sum_s \sum_c (Income_{cs} - Cost_{cs}) \times x_{cs} \quad (1)$$

$$Income_{cs} = P_c * Y_{cs} \quad (2)$$

$$Cost_{cs} = (WN_c/eff_s) \times CW + QE_{cs} \times CE + CSYS_{cs} + OIC_c \quad (3)$$

Water footprints. In this study, instead of minimizing the physical volume of water consumption, minimizing water footprint per hectare was considered. By minimizing the water footprint index, several objectives can be achieved simultaneously: decreasing water consumption, increasing water efficiency, and reducing pollution per unit of crop (Hoekstra, & Chapagain, 2011; Hoekstra *et al*., 2009).

$$WFP^{min} = \sum_s \sum_c WF_{cs} \times x_{cs} \quad (4)$$

Energy footprint. The energy footprint index is calculated with the aim of determining the amount of energy consumed (Li *et al*., 2015). Due to the importance of reducing energy consumption in applying modern irrigation systems, minimizing the energy consumption (energy footprint) per hectare, was entered in the proposed model as an objective:

$$EFP^{min} = \sum_s \sum_c EF_{cs} \times x_{cs} \quad (5)$$

CO_2 emission. The energy used for pumping and irrigation emits the significant carbon emissions, which accelerates the process of climate change and global warming. As such, this is one of three scopes of CSA to reduce or eliminate the greenhouse gas emissions in the agricultural sector. Thus, minimizing CO_2 emissions was considered

Water Footprint

To effectively manage water resources as well as to minimize the water consumption, it is essential to define appropriate criteria and integrate them into support tools and decision-making models. The concept of water footprint, first was introduced by Hoekstra as a quantitative measure of the water volume consumed per unit of crop as well as the volume of water required to dilute pollution (Hoekstra and Chapagain, 2011). Green, blue, gray, and white water footprints for wheat, rice, tomato, barley, and forage corn in the study area were estimated using the proposed framework developed by Ababaei & Etedali (2014). The green water footprints represent part of the total evaporative flow allocated to human purposes, whereas the blue water footprints represent the volume of groundwater and surface water consumed for the human requirements. Besides, the volume of water required to dilute wasted manure (using runoff or deep infiltration) indicates a gray water footprint. In this study, following most studies, the gray water footprint was calculated only for nitrogen fertilizers as the most important source of agricultural land pollution in Iran (Ashktorab & Zibaei, 2021). At the end, the white water footprint was also calculated based on the proposed method by Ababaei & Etedali (1).

Multi-objective Model

A multi-objective optimization model was developed to determine a Water-Energy-Climate Smart Agriculture Model called 'WECSAM'. For this purpose, some conflicting but vital objectives were set for the smart allocation of water and land resources between wheat, barley, rice, tomato, and forage corn in the study area. In this model, the system profit, water footprint, CO_2 emissions, and energy footprint can be optimized with regard to water and land resources constraint in different irrigated water seasons. Each crop was entered into the model in six separate activities, depending on the irrigation system. Besides, the technical coefficients and available resources for water and land inputs were calculated by planting season, and reproductive process of genetic algorithm was described by the following steps: producing a population of chromosomes, evaluation of the fitness, forming a loop to generate new population, repeating the process of selection, crossover, mutation, and accepting until the population is completed, running the algorithm using new generation, evaluation of stopping criteria (Khoshnevisan *et al*., 2015). MATLAB optimization program finds the minimum of each objective function when it solves an optimization problem. So, objective functions ought to be maximized should be multiplied by (−1) (Elsoragaby *et al*., 2020). More details about GA can be found in the literature (Collette & Siarry, 2004).

TOPSIS

After solving the multi-objective model and achieving the optimal Pareto frontier, the most effective Pareto solution can be chosen based on the different attitudes of decision makers and stakeholders, which is implemented in the TOPSIS method. This is an easy way to rank available options based on different criteria. Mentioned method that chooses the shortest distance from the ideal point as the best alternative, is one of the compromise methods (Mirzaei & Zibaei, 2020).

as another objective of this study:

$$CE^{min} = \sum_s \sum_c CO_{cs} \cdot x_{cs} \quad (6)$$

$$CO_{cs} = CEF \cdot QF_c + CEP \cdot QP_c + CEPD \cdot QPD_c + CEI \cdot QEI_c + COI \quad (7)$$

Constraints. Due to the differences in the planting season in the cultivation pattern of the region, the constraints of water and land resources were defined in different planting seasons (eq.8-eq.13). Eq. 12 is the constraint of economic output to guarantee the livelihood of farmers and economic development.

$$\sum_s \sum_c LANDS1_{cs} \times x_{cs} \leq TLS1 \quad (8)$$

$$\sum_s \sum_c LANDS2_{cs} \times x_{cs} \leq TLS1 \quad (9)$$

$$\sum_s \sum_c WATS1_{cs} \times x_{cs} \leq (SWS1 + GWS1) \quad (10)$$

$$\sum_s \sum_c WATS2_{cs} \times x_{cs} \leq (SWS1 + GWS1) \quad (11)$$

$$\sum_s \sum_c GM_{cs} \times x_{cs} \geq Prof^{min} \quad (12)$$

$$x_{csys} \geq 0$$

Genetic algorithm

Multi-objective economic-hydrologic-environmental problem solved by Genetic Algorithm (GA) method using MATLAB toolbox. Collette & Siarry (2004) refer to genetic algorithm as a "comprehensive heuristic search" that often solves complex problems that are not possible to be solved with conventional methods. The

Table 3- The nomenclature of the parameters and variables used in WECSAM model

Symbol	Definition
Indices	
c	Index of crop
s	Index of irrigation system
Max	Superscript for maximum
Min	Superscript for minimum
Decision variable	
X_{cs}	Land use allocation to crop c irrigated with system s (ha)
Objective functions	
$Profit^{max}$	Maximum system profit (10 Rials)
WFP^{min}	Minimum water footprint (m^3/ha)
EFP^{min}	Minimum energy footprint (Kw.h/ha)
CE^{min}	Minimum CO_2 emission (kg)
Parameters	
$Income_{cs}$	Income of crop c irrigated with system s (10 Rials)
$Cost_{csys}$	Costs of crop c irrigated with system s (10 Rials)
P_c	Price of crop c (10 Rials)
Y_{cs}	Yield of crop c irrigated with system s (tons)
WN_c	Water required for crop c (m^3/ha)
Eff_s	Efficiency of irrigation system s
CW	Costs of water utilization (10 Rials)
QE_{cs}	Quantity of energy use for crop c irrigated with system s (kw.h/ha)
CE	Costs of electricity utilization (10 Rials)
$CSYS_{cs}$	Costs of system for system s implemented for crop c (10 Rials/ha)
OIC_c	Other inputs costs for crop c (10 Rials)
WF_{cs}	Total water footprint of crop c irrigated with system s (m^3/ha)
EF_{cs}	Energy used per ha for crop c irrigated with system s (kw.h/ha)
CO_{cs}	CO_2 emissions of crop c irrigated with system s (kg co_2/ha)
CEF	Carbon emission coefficient of fertilizer utilization for crop c (kg co_2/kg)
QF_c	Fertilizer utilization amount per unit area of crop c (kg/ha)

CEP	Carbon emission coefficient of pesticide utilization for crop c (kg co_2/kg)
QP_c	Pesticide utilization amount per unit area of crop c (kg/ha)
CED	Carbon emission coefficient of diesel oil utilization for crop c (kg co_2/L)
QD_c	Diesel oil utilization amount per unit area of crop c (L/ha)
CEI	Carbon emission coefficient of electricity (kg co_2/kw.h)
QEI_c	Electricity utilization amount per unit area of crop c (kw.h/ha)
CI	Carbon emission coefficient of irrigation area (kg co_2/ha)
$LANDS1_{cs}$	Land coefficient for winter crops irrigated with system s (ha)
TLS1	Total land available for winter crops (ha)
$LANDS2_{cs}$	Land coefficient for summer crops irrigated with system s (ha)
TLS2	Total land available for summer crops (ha)
$WATS1_{cs}$	Water need of winter crops irrigated with system s (m^3/ha)
SWS	Total surface water available for winter crops (ha)
GWS	Total ground water available for winter crops (ha)
TWATS1	Total water available for winter crops (ha)
$WATS2_{cs}$	Water need of summer crops irrigated with system s (m^3/ha)
TWATS2	Total water available for summer crops (ha)
GM_{cs}	Gross margin of crop c irrigated with system s (10 Rials /ha)
$Prof^{min}$	Minimum expected profit (10 Rials)
$Area_c^{min}$	Approved minimum area allocated for crop c (ha)

Data collection and processing

The data needed to implement the WECSAM model were collected from a variety of sources, including local specialist organization, statistical yearbooks, interview with farmers and experts, and the experimental studies. The data required for the WEAP model, including climatic information of the region (maximum and minimum temperature, precipitation, relative humidity, wind speed and sunny hours) were collected from the information of Doroodzan and Zarghan synoptic stations (Meteorology Organization of Iran (IRIMO), 2020). Land use and water consumption for agriculture, industry and urban, and also soil types and groundwater resources were extracted from the reports of Fars Regional Water Organization (Regional Water Company of Fars, 2020). Information on planting and harvesting dates, irrigation and potential yield of the region was obtained from interviews with farmers and specialists of the regional agriculture department. The minimum area under cultivation for each crop is an amount approved by the Agriculture-Jahad Organization for this region, which is set at 2160 for barley, 3200 for forage corn, 2000 for rice, 960 for tomatoes, and 14400 for wheat.

The energy required to extract one cubic meter of water in different irrigation systems in the study area and the cost of each irrigation system per hectare were calculated and updated from the results of a research project conducted by Liaqat *et al*. (2012). Distribution and transfer efficiencies of the region and on-farm application efficiencies by different irrigation systems were extracted from the reports of Fars Regional Water Organization (Regional Water Company of Fars, 2020) and from the study of Abbasi *et al*. (2014), respectively. Information on prices and production costs of products was obtained from the Database of the Ministry of Agriculture-Jahad (MAJ, 2020). The amount of CO2 emissions for each product was calculated based on the study conducted by Li *et al*. (2019) which were equal to 0.9 $kgCO_2$/kg for chemical fertilizer, 4.93 $kgCO_2$/kg for pesticide, 2.73 $kgCO_2$/L for diesel oil, 0.85 $kgCO_2$/kW·h for electricity, and 740 $kgCO_2$/ha for irrigation.

Study area

The study area, irrigation network and drainage of Doroodzan, include six construction units located in the north of Bakhtegan basin on the Kor River and its gross area is 78553 hectares (as illustrated in Fig. 2).

More than 90% of the cultivation area in this region is allocated to wheat and barley crops in winter and rice, tomatoes and forage corn in summer. Fig. 1 depicts the geographical location of the study area۲

Results

Irrigation systems, CO_2 emissions, water footprints and energy footprints

Table 4 reports the values of efficiencies for different irrigation systems. In Doroodzan region, transfer and distribution efficiencies are 0.88 and 0.78, respectively, but the application efficiency at farm level varies depending on the irrigation system used in the field. The efficiency of the surface irrigation system in this area is calculated 0.58, whereas it is equal to 0.71 for the drip irrigation system, and is equal to 0.52 for the classic permanent sprinkler irrigation system. Semi-portable and center-pivot sprinkler irrigation systems are 0.65. In the improved surface irrigation system, due to the improvement of distribution efficiency up to 90%, the total irrigation efficiency could reach at 0.46, known as the highest efficiency among different systems after drip irrigation. The amount of electricity consumption per cubic meter of water in each of the different irrigation systems is provided in the last column of Table 4.

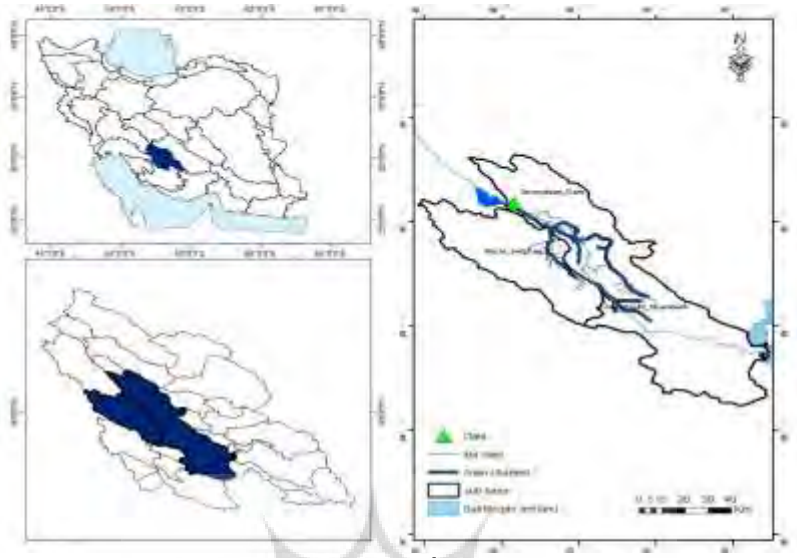


Fig. 2- Location of study area

Table 4- Transfer, distribution, farm irrigation and total efficiency and energy use of per m3 water extraction

	Irrigation systems	Transfer	Distribution	Farm	Total	Energy (kw.h)
Sys1	Surface	0.88	0.78	0.58	0.40	0.30
Sys2	Surface-improved	0.88	0.90	0.58	0.46	0.30
Sys3	Drip	0.88	0.78	0.71	0.49	0.70
Sys4	Sprinkler-permanent	0.88	0.78	0.52	0.36	1.33
Sys5	Sprinkler-semi permanent	0.88	0.78	0.65	0.45	1.09
Sys6	Sprinkler-center pivot	0.88	0.78	0.65	0.45	0.89

Source: Regional water Company of Fars

The highest energy consumption is related to the classical fixed sprinkler irrigation system, followed by semi-portable sprinkler irrigation. Moreover, the lowest energy consumption is related to the surface irrigation system that is considered 0.4 less than drip irrigation system, based on literature (Zhao *et al*., 2020).

In Table 5, the total water footprint per ha calculated for each crop and each system. The highest and lowest amount of water footprint were obtained for rice and barley, respectively. Tomato was ranked the second in terms of water footprint. Comparison of water footprints between crops and irrigation systems shows that the highest water footprint was obtained in the surface irrigation system, whereas the lowest one was for drip irrigation system. Regarding that both the yield and the amount of water consumption were involved to calculate the water footprint, we could expect that the drip irrigation system potentially has the lowest amount of water footprint among different crops.

The results of energy footprint per ha are listed in Table 6. The rice and barley contained the highest and the lowest energy footprint per ha respectively.

Table 5- Total water footprint of selected crops by different irrigation systems (m3/ha)

	Irrigation systems	Barley	Forage corn	Rice	Tomato	Wheat
Sys1	Surface	8866.25	9754.34	30401.95	24262.63	10303.61
Sys2	Surface-improved	7941.91	6780.05	24674.64	19353.89	7256.08
Sys3	Drip	5657.40	6381.86	23299.66	18291.49	6904.39
Sys4	Sprinkler-permanent	7794.24	8782.90	31768.71	25007.10	9467.31
Sys5	Sprinkler-semi permanent	6345.07	7138.74	25591.14	20104.54	9416.43
Sys6	Sprinkler-center pivot	8131.89	8925.56	27377.96	21891.36	9416.43

Source: Research Findings

Table 6- Energy footprint of selected crops under different irrigation systems (Kwh/ha)

	Irrigation systems	Barley	Forage corn	Rice	Tomato	Wheat
Sys1	Surface	2079.77	2346.19	8540.48	6698.68	2510.97
Sys2	Surface-improved	1802.47	4744.53	17270.74	13546.22	5077.75
Sys3	Drip	3958.68	4465.80	30886.65	24225.79	9080.94
Sys4	Sprinkler-permanent	10264.45	11579.36	42150.50	33060.53	12392.61
Sys5	Sprinkler-semi permanent	8240.02	9295.61	33837.31	26540.12	6657.24
Sys6	Sprinkler-center pivot	5514.00	6220.37	22643.01	17759.93	6657.24

Source: Research findings

Table 7- CO_2 emission of selected crops under different irrigation systems (kgCO_2/ha)

	Irrigation systems	Barley	Forage corn	Rice	Tomato	Wheat
Sys1	Surface	3058.58	3641.68	8601.83	7266.48	3500.45
Sys2	Surface-improved	2822.87	5680.26	16022.56	13086.89	5682.21
Sys3	Drip	4655.65	5443.35	27596.09	22164.53	9084.93
Sys4	Sprinkler-permanent	10015.55	11489.87	37170.36	29674.06	11899.85
Sys5	Sprinkler-semi permanent	8294.80	9548.68	30104.14	24131.71	7024.78
Sys6	Sprinkler-center pivot	5977.68	6934.73	20588.99	16668.55	7024.78

Source: Research findings

The results for CO_2 emission per hectare for crops with different irrigation systems are reported in Table 7. A comparison between the emission of per hectare of different crops shows that rice has the highest and barley has the lowest amount. However, all crops reach their maximum emission amount when irrigated with the permanent sprinkler irrigation, and the use of improved surface irrigation diffuses the lowest emission compared to other irrigation systems.

Results of single-objective models

Four objective functions were considered to determine the optimal cropping pattern, which simultaneously involved the choice of irrigation method. To obtain a clearer analysis, we first implemented four single-objective model in GAMS software separately. The results of single-objective models are depicted in Table 8. As can be observed, if the cropping pattern of this region is determined only with the objective of maximizing economic profit then products like barley, forage corn, and rice will enter the pattern at the minimum approved cultivation area for the region, and therefore only tomato and wheat compete with each other in allocation of the cropping area. The results indicate that in order to maximize profit, the total cultivation area of the selected crops will be 54,295 hectares, in which 4% will be allocated to barley, 5.9% to forage corn, 3.7% to rice, 11.2% to tomatoes, and 75.2% to wheat. To irrigate this pattern, 3.7% improved surface irrigation system, 21.1% the drip irrigation, and 75.2% the semi-portable sprinkler irrigation would be utilized. The rice will be irrigated with the improved surface irrigation, whereas barley, forage corn, and tomatoes will be irrigated with the drip irrigation, and finally wheat will be irrigated with semi-portable sprinkler irrigation.

If the objective of cropping pattern selection in the study area, is to minimize the greenhouse gas emissions, then 2160 hectares of barley with the improved surface irrigation system, 13298 hectares of forage corn, 200 hectares of rice with surface irrigation system, 960 hectares of tomatoes with the drip irrigation system, and 34281 hectares of wheat with the surface irrigation system are included in the cropping pattern. As such, in this case, most of the cultivation area is irrigated using a surface irrigation system. In this case, 52698.8 hectares of the region's arable lands are cultivated with the selected crops, in which 68.8% are irrigated with the traditional surface irrigation system, 4.1% with the improved surface irrigation system, and 27.1% with the drip irrigation system. Wheat includes for 65.1% of the cultivation area, followed by forage corn (25.2%), barley (4.1%), rice (3.8%) and tomatoes (1.8%). Another very important objective in the current situation of the world and also study area is to minimize the water consumption. In this regard, if the cropping pattern is determined only by minimizing the water footprint, 2160 hectares of barley, 9339 hectares of forage corn, 2000 hectares of rice, 3302 hectares of tomatoes, and 14400 hectares of wheat will be included in the pattern. However, all crops except rice are irrigated using the drip irrigation system, whereas only rice enters the pattern using the improved surface irrigation system. In this case, the total cultivation area of these crops will be 31201.3 hectares, in which wheat contains the highest share with 46.2%, whereas rice with 6.4% obtains the lowest share in the cropping pattern. Besides, 29.9% of this area is forage corn, 10.6% is tomato, and 6.9% is barley.

The fourth considered objective is to minimize the energy consumption in the selected cropping pattern of Doroodzan region. To do so, the problem is solved with the aim of minimizing the energy consumption and water and land restrictions, as well as the constraint of minimum economic profit. The cropping pattern to meet this objective for cultivation includes 28,667 hectares of barley with the improved surface irrigation, 12822 hectares of forage corn with the drip irrigation, and 2000, 960, 19468 hectares of rice, tomato and wheat crops with the traditional surface irrigation, respectively. In this cropping pattern, a total area of 63,916.6 hectares is allocated to cultivate these crops, in which 48,135 hectares are allocated to winter crops including wheat and barley, while 15,781.6 hectares to summer crops including forage corn and rice. The share of surface, improved surface and drip systems will be 35.1, 44.9, and 20.1 percent, respectively. As a result, the sprinkler irrigation systems are not proposed to minimize the energy consumption.

Table 8- Optimized cropping pattern in single objective models

		sys1	sys2	sys3	sys4	sys5	sys6
Model 1: Profit Maximizing	Barley	-	-	2160.0	-	-	-
	Forage corn	-	-	3200.0	-	-	-
	Rice	-	2000.0	-	-	-	-
	Tomato	-	-	6094.6	-	-	-
	Wheat	-	-	-	-	40840.4	-
Model 2: Emission Minimizing	Barley	-	2160.0	-	-	-	-
	Forage corn	-	-	13298.3	-	-	-
	Rice	2000.0	-	-	-	-	-
	Tomato	-	-	960.0	-	-	-
	Wheat	34280.7	-	-	-	-	-
Model 3: WFP Minimizing	Barley	-	-	2160.0	-	-	-
	Forage corn	-	-	9339.2	-	-	-
	Rice	-	2000.0		-	-	-
	Tomato	-	-	3302.1	-	-	-
	Wheat	-	-	14400.0	-	-	-
Model 4: EFP Minimizing	Barley	-	28666.7	-	-	-	-
	Forage corn	-	-	12821.6	-	-	-
	Rice	2000.0	-	-	-	-	-
	Tomato	960.0	-	-	-	-	-
	Wheat	19468.3	-	-	-	-	-

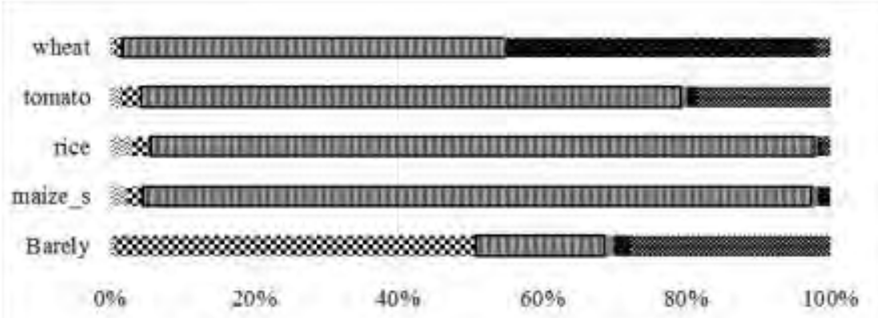
Source: Research Findings

Results of Multi-objective WECSAM Model

After comparing the results of four single-objective models, we considered the results of multi-objective models obtaining from the GA implementation. By running this model in MATLAB, the Pareto frontier curve was obtained with 70 solutions, in which the most effective Pareto solution was selected using the TOPSIS method and equal weighting of each objective as criteria (Fig. 3).

The energy-smart, water-smart, and climate-smart cropping pattern was obtained for Doroodzan region contains 59% wheat, 11.6% tomatoes, 4.7% rice, 7.5% forage corn, and 17.2% barley. The results of WECSAM model suggest that only 54.5% of the arable lands in Doroodzan region should be irrigated with the drip irrigation system. After the drip irrigation, the semi-portable sprinkler irrigation contains the largest share of the irrigation area in the region. The improved surface irrigation system will irrigate 10%, whereas the center-pivot sprinkler will irrigate 8% of the cultivation area.

At the meantime, the traditional irrigation system and the permanent sprinkler irrigation will contribute less than one percent to the irrigation of the cultivation area. A general comparison between the obtained results indicates that the most selective irrigation system is the drip irrigation system, which is the predominant irrigation method for forage corn, rice, tomato, and wheat crops, while the predominant irrigation method for barley is the improved surface irrigation system. On the other hand, the predominant irrigation method after the drip irrigation is the semi-portable sprinkler system for wheat. Besides, the center-pivot irrigation system is the second choice for irrigation for barley and tomatoes. Overall, the drip irrigation system, semi-portable sprinkler irrigation system, and the improved surface irrigation system obtain the highest cultivation area, respectively. In addition, the classical fixed sprinkler irrigation system, the surface irrigation system, and the center pivot sprinkler system obtain the least share in the irrigation of the chosen cultivation pattern.



	Barely	maize_s	rice	tomato	wheat
sys1	44.98	80.88	65.07	72.75	129.78
sys2	3978.99	71.13	55.12	157.36	306.51
sys3	1415.57	3233.26	2003.88	4021.89	14441.19
sys4	105.49	28.56	9.27	43.98	50.04
sys5	176.89	46.34	7.97	73.66	11771.12
sys6	2200.19	10.42	27.33	987.10	483.79

Fig. 3- Allocated land to selected crops under different irrigation systems in WECSAM

Comparing the values of different objective functions in four single-objective models can provide a trade-off analysis between different objectives (Fig. 4). Obviously, the highest economic benefits are obtained in Model 1, whereas in other models, the objectives are to minimize the water and energy footprints and CO_2 emissions, the solution is determined in such a way that can provide the minimum profit constraint, because the increase in profit is the result of increasing levels of agricultural activity, which is not possible except at the cost of more water and energy consumption, and more CO_2 emissions.

Regarding the amount of CO_2 emissions, the highest value is related to the profit maximization model, whereas the lowest one is related to the emission minimization model. In models 3 and 4, the amount of emission is near to the model 2, but in the case where the objective is to minimize the water footprint, the emission is higher than the case of the energy minimization. Thus, it can be concluded that water footprint and CO_2 emission are inversely related to each other.

The highest amount of water footprint belongs to model 4, followed by models 1, 2 and 3, respectively, so that the difference between the amounts of water footprint in model 3 with other models is very large. Eventually, the amount of energy consumed was the highest in Model 1 and the lowest in Model 4. It can be seen that after model 1, the highest energy consumption is in the case where our objective is to minimize the water footprint. Accordingly, achieving the minimization of the objectives of water footprint and energy footprint can move against each other.

Conclusion

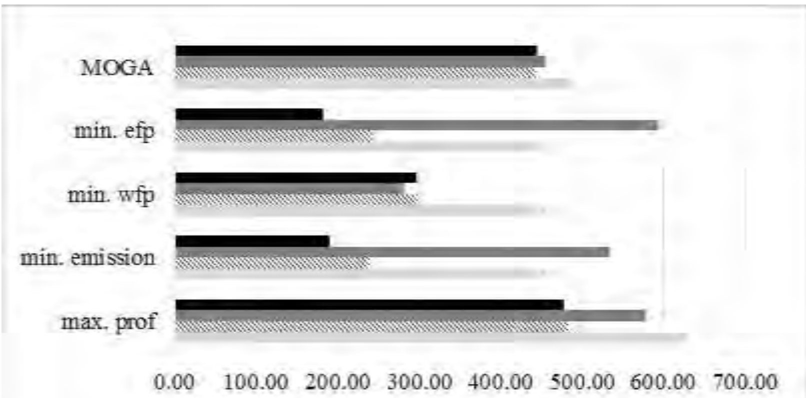
An integrated hydrological-economic-environmental model so-called WECSAM was developed to ensure the obtaining a climate-smart, water-smart and energy-smart cropping pattern. This model included the WEAP hydrological model as a basin database, a multi-objective model in the context of CSA for simultaneous optimization of profits, CO2 emissions, water and energy footprint, and a multi-criteria model called TOPSIS .This model contains the following advantages:

- Simultaneous optimization of cropping pattern and irrigation system so that it includes adaptation, mitigation, and productivity strategies, simultaneously.
- The use of a hydrological simulation model for a basin to more accurately calculate uncertain parameters, including available water, water requirements, and crop yield.
- Applying the concept of water footprint instead of the physical amount of water in order to achieve multiple objectives (decreasing water consumption, increasing water efficiency, and reducing pollution per unit of crop) by minimizing one objective.
- Determining the allowable limit for the

development of new irrigation methods so that the benefits of improving efficiency and the disadvantages of increasing energy consumption, and CO_2 emissions are adjusted.

- Balancing the consumption of water, energy, and land resources in the agricultural system in different growing seasons

The possibility of trade-off analysis between four objectives of the model.



	max. prof	min. emission	min. wfp	min. efp	MOGA
efp	476.91	189.70	295.56	181.33	444.23
wfp	578.04	533.60	280.99	594.18	455.41
emission	481.50	236.96	296.95	243.04	442.01
profit	628.42	455.56	455.56	455.56	488.99

Fig. 4- Comparison of objective values in single-objective and multi-objective models

the conflicting manner of the proposed objectives. This result is in accordance with ones obtained by Daccache *et al*. (2014) and Jacobs (2006). The result of the WECSAM multi-objective model indicates that by simultaneously optimizing the conflicting objectives of maximizing profit and minimizing water, energy, and CO_2 emissions, as compared to the single-objective model of maximizing economic profit, the water footprint decreases by 8.2%, Energy footprint decreases by 21.2%, CO_2 emissions by 6.9%, and profit decreases by 7.4%. In this pattern, the share of drip systems is 54.5%, and for semi-permanent sprinkler system it is 26.2%, whereas the classic permanent sprinkler system contains less than one percent of the irrigation of the chosen cropping pattern. The selection of irrigation systems resulted from WECSAM model is in accordance with the results of the study conducted by Mushtaq *et al*. (2015). Thus, deciding based on an integrated WECSAM model can well support the decision to adopt more efficient irrigation technologies at basin level and to manage it in a way that the potential negative effects (such as CO_2 emissions and more energy consumption) along with positive effects (reducing water footprints) be considered.

The WECSAM model was implemented for the northern region of Bakhtegan basin called Doroodzan irrigation network. First, the water footprint was calculated for different crops using the results of the simulation of the WEAP-MABIA model for the region. In the surface irrigation system, the highest amount of the water footprint per hectare is for rice and then tomatoes, in which the barley crop contains the lowest amount of the water footprint per hectare. The obtained results for the water footprint of the crops are in accordance with the results of Ashktorab & Zibaei (2019). Comparing the water footprint of each crop in different irrigation systems, the results indicate that the lowest amount of this index is attained for all crops in the drip irrigation system, which is due to higher yield and less water consumption in this system. This result of the effect of the drip irrigation system on reducing the water footprint is in accordance with the study of Nouri et al. (Nouri et al., 2016).

Trade-off analysis between objectives using a comparison of the results of single-objective models reveal that the values of the energy footprint and water footprint in the respective models change against each other and this appears such as rice and tomatoes are very rare to grow using a sprinkler irrigation system. Hence, the justification for this choice using a mathematical model lacks any technical support. In an experimental analysis, it can be explained that in the area of maximum allowable cultivation area using mentioned irrigation methods that can be allocated to these crops, will be equal to these values. Nevertheless, it can be recommended that in future studies, technical principles for choosing the appropriate irrigation system for each crop should be included in the model.

The results of WECSAM show that achieving the climate-smart agriculture goals in the Doroodzan irrigation network is not necessarily possible by changing the irrigation technology of all crops to the modern irrigation system, but by optimizing cropping patterns under different irrigation systems and determining allowable limits to develop modern irrigation systems at the basin level can achieve the goals of climate-smart agriculture.

As can be observed, the GA selects the cropping pattern in such a way that all crops enter the pattern using all irrigation systems. Some crops

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بهینه‌سازی الگوی کشت در چارچوب اهداف کشاورزی اقلیم-هوشمند: مطالعه موردی شبکه آبیاری درودزن- ایران

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چکیده

سیستم‌های نوین آبیاری به عنوان یک راهبرد انطباقی برای مدیریت اثرات تغییر اقلیم و بهبود امنیت آب در نظر گرفته می‌شود. استفاده از چنین سیستم‌هایی علاوه بر صرفه‌جویی در مصرف آب، چالش‌هایی را در زمینه افزایش مصرف انرژی و انتشار گازهای گلخانه‌ای ایجاد کرده است. اگرچه برخی از مطالعات اخیر تحلیل‌های ارزنده‌ای از رابطه بین آب و انرژی در سیستم‌های آبیاری کشاورزی ارائه کرده‌اند، اما توجه همزمان به بهره‌وری، سازگاری و کاهش اثرات مخرب محیط زیستی در بهینه‌سازی الگوی کشت یک سیستم کشاورزی به عنوان یک ضرورت اساسی کمتر مورد توجه قرار گرفته است. کشاورزی اقلیم-هوشمند به عنوان یک مفهوم برنامه‌ای قوی که به این سه هدف می‌پردازد، پتانسیل یک راه‌حل برد سه‌جانبه را ایجاد کرده است. این مطالعه با توسعه یک مدل یکپارچه اقتصادی-هیدرولوژیکی-محیط‌زیستی به نام WECSAM در سطح حوضه، متشکل از یک مدل هیدرولوژیکی به نام WEAP و یک مدل بهینه‌سازی چند-هدفه و ترکیب آن با مفاهیم ردپای آب، ردپای انرژی و انتشار گازهای گلخانه‌ای در چارچوب کشاورزی اقلیم-هوشمند، در جهت پر کردن این خلأ است. این مدل برای منطقه شمالی حوضه آبریز بختگان به نام شبکه آبیاری درودزن اجرا شد. نتایج مدل WECSAM نشان داد که با بهینه‌سازی همزمان اهداف متناقض حداکثرسازی سود اقتصادی و حداقل‌سازی ردپای آب، ردپای انرژی و انتشار دی‌اکسید کربن، در مقایسه با مدل تک-هدفه حداکثرسازی سود، باعث کاهش ۸/۲ درصد ردپای آب، کاهش ۲۱/۲ درصد ردپای انرژی، کاهش ۶/۹ درصد انتشار انتشار دی اکسید کربن و کاهش ۷/۴ درصد سود اقتصادی می‌شود. سهم سیستم قطره‌ای در آبیاری الگوی کشت آب-هوشمند، انرژی-هوشمند و اقلیم-هوشمند ۵۴/۵ درصد و برای سیستم بارانی نیمه متحرک ۲۶/۲ درصد است، در حالی که سیستم بارانی کلاسیک ثابت کمتر از یک درصد از آبیاری الگوی کشت بهینه را به خود اختصاص می‌دهد.

واژه‌های کلیدی: سیستم‌های آبیاری، الگوی کشت، کشاورزی اقلیم-هوشمند، بهینه‌سازی چندهدفه، رد پای آب، انتشار CO_2

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