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Authors
Arefinia, Ali
Bozorg-Haddad, Omid
Ahmadaali, Khaled
et al.

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ORIGINAL PAPER

Cropping patterns based on virtual water content considering water and food security under climate change conditions

Ali Arefinia[1] · Omid Bozorg-Haddad[1] · Khaled Ahmadaali[2] · Babak Zolghadr-Asli[3,4] · Hugo A. Loáiciga[5]

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Abstract
This paper presents a multipurpose optimization algorithm (MOA) to optimize crop patterns under climate change, minimizing water use and maximizing crop revenue while enforcing food security and regional water security constraints. An application of the MOA yields a total of 12 Pareto fronts for 20-year horizons centered on 2030, 2050, 2070, and 2090 under representative concentration pathways (RCPs) 2.6, 4.5, and 8.5, each of which is associated with specific land use conditions. The results show that crop production must increase due to population growth. However, climate projections for the study region in eastern Iran indicate unsuitable conditions to support the incremental production. This paper's optimization results show that 89%, 73%, and 48% of optimal crop production are achievable considering food-safety constraints in 20-year periods centered on 2050, 2070, and 2090, respectively. This paper's results indicate that revenue would increase, water use would decline, and environmental sustainability would be reached in the study area under the optimized cropping patterns.

Keywords Virtual water · Climate change · Statistical downscaling model · Water security · Food security · Optimization

1 Introduction

Climate change caused by human activity causes environmental degradation, reduction in agricultural production, and food insecurity in developing countries. Billions of people might face severe water shortages and food insecurity. Therefore, appropriate solutions must be adopted by countries at risk to ensure food security, prevent water security from being compromised, and optimize the use of water resources to meet the multifaceted goals of water users and policy makers while securing a sustainable environment (FAO 2015).

Water scarcity is a widespread concern in arid and semi-arid countries (Misra 2014). Improper water management in some areas would expose two-thirds of the world's

✉ Omid Bozorg-Haddad
OBHaddad@ut.ac.ir

Extended author information available on the last page of the article

population into a state of water stress by 2025 (FAO 2018). Water shortages and water stress in the Middle East are projected to increase by 2050 (FAO 2017). In total, 70% of the total freshwater existing on the earth is used in the agricultural sector (World Bank Group 2016, USGS 2016), which poses challenges concerning water supply for agriculture in many parts of the world, especially under climate change (USGCRP 2017) and population growth. Climate change significantly impacts agricultural water resources (Parry and Rosenzweig 1990; Arnell 2004; Piao et al. 2010). Therefore, determining and assessing the impacts of climate change on agricultural water use is a timely priority to devise management strategies.

Optimization models have proven to effectively manage water resources and agricultural land use. Numerous models have been developed to allocate water resources and agricultural land with optimization techniques such as linear programming, nonlinear programming, dynamic programming, and evolutionary and meta-heuristic algorithms (Bozorg-Haddad et al. 2009; Singh 2012; Su et al. 2014; Akbari-Alashti et al. 2014; Davijani et al. 2016; Ye et al. 2018; Oliazadeh et al. 2021).

Previous studies have often focused on managing water resources and agricultural land with optimization models that maximize revenue under historic-climate conditions (Adams et al. 1990; Parry and Rosenzweig 1990; Fischer et al. 2005; Howden et al. 2007); however, they neglect water security, food security, the role of virtual water in the context of food security, and climate change. Virtual water is the amount of that substance used in the production of a good, for instance, in the production of crops. In this case it is expressed as a volume of water per unit weight of produce, say, in cubic meters per kilogram of produce. The concept of virtual water content (VWC) is currently considered one of the components of water efficiency in the water industry (Arefinia et al. 2021). The VWC concept is a helpful tool in evaluating water use and achieving water and food security, especially under climate change conditions.

To the knowledge of these authors a comprehensive model for designing a cultivation or cropping pattern considering the concepts of food security, water security, and the VWC under climate change conditions has not been provided yet. This paper addresses this knowledge gap by presenting an approach to choosing cropping patterns considering the impacts of climate change on water and food security, and considering the concept of virtual water under climate change conditions. This paper's methodology is applied to a study area in eastern Iran.

2 Methods

The methodology presented in this paper includes two phases: (1) preparing datasets for four time horizons (2020–2039 or 2030s, 2040–2059 or 2050s, 2060–2079 or 2070s, and 2080–2099 or 2090s) under three representative concentration pathways (RCPs) and (2) land use planning with multiobjective optimization addressing water and food security. The employed methodology is graphically depicted in Fig. 1.

2.1 Preparing the datasets for climate change conditions

2.1.1 Virtual water content (*VWC*) and yield datasets

Virtual water and product yield data under climate change were obtained in three stages:

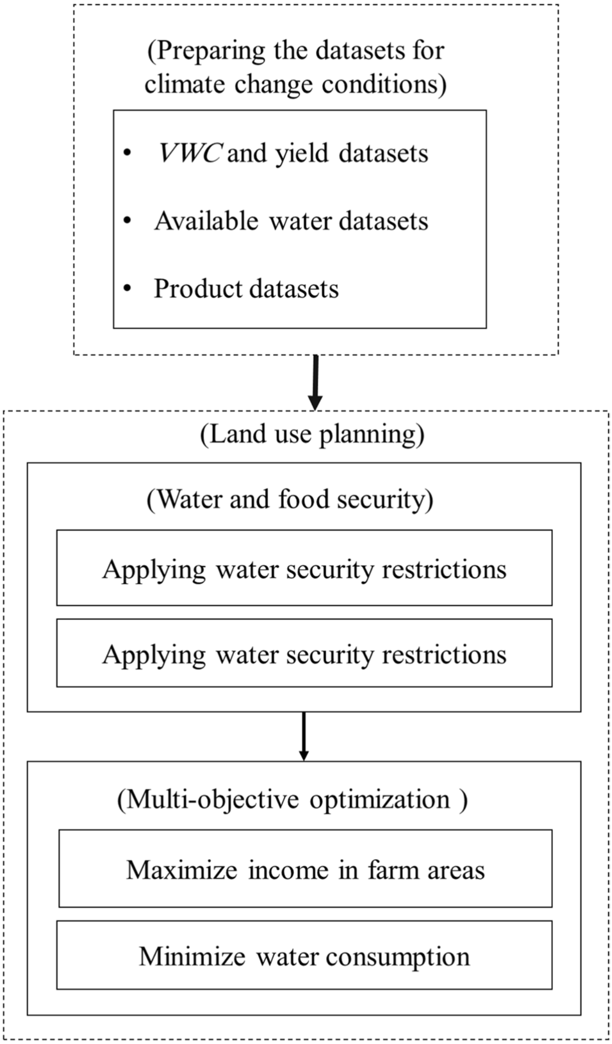

Fig. 1 Flowchart of methodology

1. The virtual water content of the studied crops in a baseline period (1986–2005) is calculated relying on meteorological and crop yield data in a study area as follows (Allen et al. 1998).

$$\mathrm{VWC} = \frac{\mathrm{CWR}}{Y} \tag{1}$$

   where VWC = virtual water content (m^3/kg), CWR = crop water requirement of crops (m^3/ha), and Y = average annual product yield (kg/ha).

2. Meteorological data under climate change conditions were forecasted in three steps. The first step is selecting a scenario to predict the field condition. In the second stage, the earth's climate is simulated with climate models according to the baseline scenario

corresponding to state 1 (period 1986–2005). These climate predictions are made with general circulation models (GCMs) featuring relatively coarse spatial resolution. The third step is to downscale the GCM climate predictions to regional scales. Daily mean surface air temperature and precipitation parameters under climate change were obtained with the CanESM2 model and downscaled with a statistical downscaling model (SDSM, Wilby et al. 2002) for RCPs 2.6, 4.5, and 8.5.

3. The results obtained in the preceding stages are applied to calculate the virtual water use and crop yields under climate change conditions by applying the support vector machine (SVM) data mining tool reported by Arefinia et al. (2021), whose approach to calculate the *VWC* and yield data under climate change conditions is depicted in Fig. 2.

2.1.2 Available water datasets for water security

One of the key indicators in assessing the status of water resources was introduced by the United Nations' Commission on Sustainable Development (UN) (Lawrence 2002). The United Nations Commission on Sustainable Development uses the rate of harvesting of its renewable water resources in each country as an index of its water conditions. A country faces a severe water crisis whenever it harvests more than 40% of its renewable water resources. The crisis is moderate if the index is between 20 and 40%. There is a balance

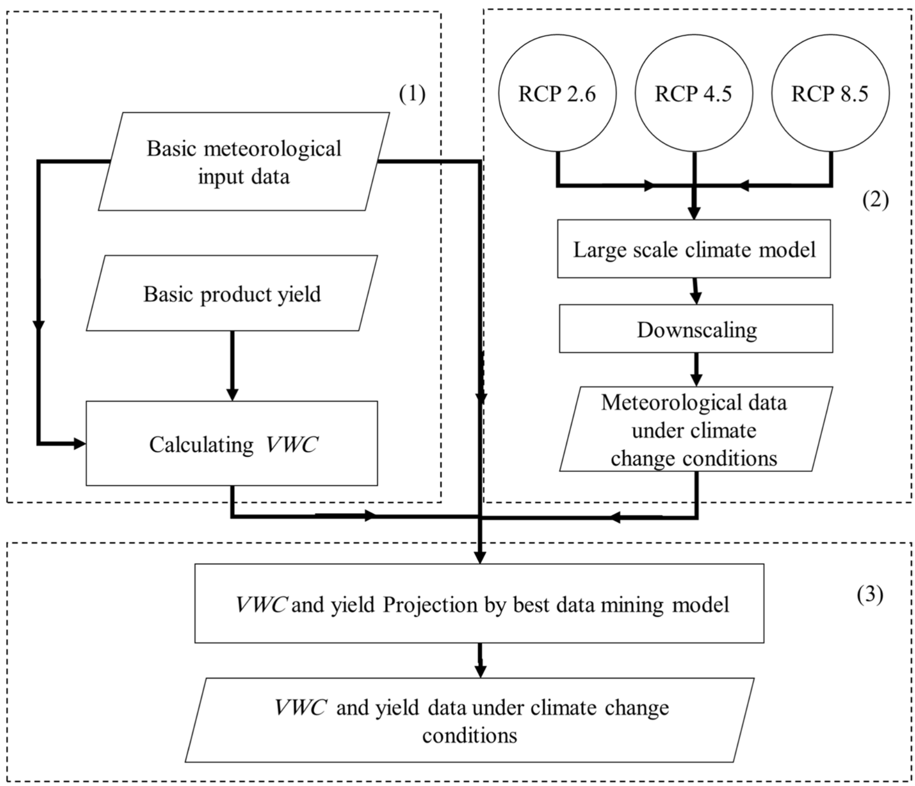

Fig. 2 Schematic of the methods used to calculate the *VWC* and crop yield data under climate change conditions (data from Arefinia et al. 2021)

between water use and water availability when the index ranges between 10 and 20%. There is no water crisis but, rather, a water surplus if the harvesting index is less than 10%.

About 70% of the annual precipitation is converted to evaporation on a global scale. This study uses the current rainfall rate for evaporation of the investigated region to calculate the available water volume. Evaporation projections under future climate change conditions are not available; therefore, this study assumes that the future evaporation rate is close to the current condition in the investigated region, and this assumption underlies our technical approach.

2.1.3 Product datasets for food security

Various factors affect food security, and assessing a region's food security must include all factors. Food security is defined as: "A situation in which everyone has access to adequate, safe and nutritious food, at all times, in terms of physical and economic health to meet their nutritional needs and preferences for an active and healthy life" (WFS: World Food Summit 1996). FAO statistics indicate that the daily per capita income varies widely worldwide (FAO 2015). Some countries, such as Iran, do not exhibit food insecurity measured by their food production and supply capacity, but, instead, by inadequate food distribution, monetary inflation, unemployment, and low purchasing power. This study assesses food security in terms of four primary crops, namely, wheat, barley, alfalfa, and maize, in four eastern provinces of Iran, considering the increasing population and climate change in 2030, 2050, 2070, and 2090.

2.2 Land use planning

Comprehensive planning of crop pattern preparation in this study was conducted in two stages. In the first stage, issues related to the optimization model and objective functions are resolved. Water and food security constraints are applied to the optimization in stage two.

2.2.1 Optimization model

The use of evolutionary optimization algorithms today in solving water resource optimization problems is widespread. The NSGA-II is an evolutionary algorithm that solves multi-objective optimization problems (Deb 1999). The optimization process of the NSGA-II has five steps: (1) a random population of chromosomes (i.e., possible solutions) is generated in the first iteration, (2) objective performance values of all the chromosomes are calculated and evaluated, and (3) the best chromosomes (parent solutions) are selected using a selection operator based on two criteria: (a) rank and (b) crowding distance (Fallah-Mehdi Pour et al. 2012; Sarzaeim et al. 2017). Chromosomes that dominate others are passed on to the next generation as parents. Otherwise, the chromosomes that are more crowded become parent solutions in the new generation of possible solutions. (4) Employ a crossover operator (Deb and Agrawal 1995), and (5) employ a mutation operator (Deb and Goyal 1996). Steps (4) and (5) generate offspring (new solutions) that are added to parent solutions in step (3) to form the next generation of possible solutions in each algorithmic iteration. The possible solutions are improved from one generation to the next until a stopping criterion is satisfied in the algorithmic search for an optimal solution.

Two general-purpose objective functions are considered in this study's optimization problem. Firstly, the amount of virtual water consumed in the study region is minimized, and, secondly, the sum of the area farms' income is maximized. The objective functions and applied constraints are listed in Eqs. (2–5):

Minimize virtual water use:

$$\min f_1 = \sum_{i=1}^{I} \sum_{j=1}^{J} \mathrm{VWC_{ij}}.Y_{\mathrm{ij}}.A_{\mathrm{ij}} \quad (2)$$

Maximizing the sum of the farm areas' income:

$$\min f_2 = \sum_{i=1}^{I} \left[\sum_{j=1}^{J} \left(T_{\mathrm{ij}}.Y_{\mathrm{ij}}.A_{\mathrm{ij}} \right) \right] \quad (3)$$

Subjected to:

$$\sum_{j=1}^{J} A_{\mathrm{ij}} \leq k \cdot \mathrm{at_i} \text{for all } i = 1, 2, \ldots, I \text{ and } j = 1, 2, \ldots, J \quad (4)$$

$$A_{ij} \geq 0 \text{for all } i = 1, 2, \ldots, I \text{ and } j = 1, 2, \ldots, J \quad (5)$$

where f_1 = total amount of virtual water used to produce the crops under study (m^3); f_2 = total sum of income of farm areas (Iranian Rials), $\mathrm{VWC_{ij}}$ = amount of virtual water in crop j in farm area i (m^3/kg), $\mathrm{A_{ij}}$ = area of crop j in farming area i (ha), i = farming area index; I = the number of farming areas (56 in this study), j = crop index, J = number of crops (4 in this study); at_i = area available for cultivation of all crops in the farming area i under current climatic conditions (ha), Y_{ij} = j yield of crop j in the farming area i (kg/ha), k = upper limit coefficient of cultivated area (a fraction specified by expert opinion), and T_{ij} = average annual revenue from of crop j in farm area i (Iranian Rial).

2.2.2 Water and food security

The amount of available water in each farming area is calculated. The magnitude of the UN severe water crisis index (i.e., using more than 40% of the total available water constitutes a severe crisis) is imposed as a constraint according to Eq. (6).

$$\sum_{j=1}^{J} \mathrm{VWC_{ij}} \bullet \mathrm{Yi}_j \bullet A_{\mathrm{ij}} \leq \mathrm{WT_i} \text{ for all } i = 1, 2, \ldots, I \text{ and } j = 1, 2, \ldots, J \quad (6)$$

where $\mathrm{VWC_{ij}}$ = amount of virtual water of crop j in farm area i (m^3/kg), A_{ij} = area of crop j in the farm area i(ha), Y_{ij} = yield of crop j in farm area i under climate change in (kg/ha), and WT_i = usable water based on the water safety index (m^3).

Food security considerations are expressed for wheat, barley, alfalfa, and maize. Food supply for four eastern provinces of Iran featuring population growth is a particular concern. Accordingly, the sum of these provinces' cereals productions in the horizons of the 2030s, 2050s, 2070s, and 2090s is imposed as food security constraints:

$$\sum_{i=1}^{I} Y_{ij} \bullet A_{ij} \leq W_j \text{ for all } i = 1, 2, \ldots, I \text{ and } j = 1, 2, \ldots, J \quad (7)$$

where A_{ij} = area under crop j in farm area i(ha), Y_{ij} = yield of crop j in farm area i under climate change (kg/ha), and W_j = minimum production of crop j with regard to food security (kg).

3 Case study

The study area consists of 4 eastern provinces (North Khorasan, Khorasan Razavi, South Khorasan, and Sistan-Baluchestan), encompassing 56 farm areas. The study region has an area of about 424,455 square kilometers, located between 55° 42′ and 63°28′ east longitude, and between 25°6′ and 38° 33′ north latitude (Fig. 4). The average elevation of the study region is 1200 m above sea level. The elevations of the study region include the eastern part of the Alborz mountain chain and the highlands of eastern Iran.

The mean annual temperature increases from north to south within the study area. The average annual temperature varies from 12 °C in the mountainous areas of North Khorasan Province to 29 °C in the coastal areas of Sistan-Baluchestan province. The mean long-term annual precipitation varies from more than 400 mm in the northern latitudes to less than 100 mm in the southern latitudes and the Oman sea coast. The average surface air temperature and mean precipitation projections under climate change are shown in Table 1.

The areas of wheat, barley, alfalfa, and maize under cultivation are 16%, 25%, 9%, and 17% of the total area under cultivation in Iran, respectively, and their yields represent, respectively, 11%, 18%, 13%, and 17% of Iran's total cereal production. The crop yields and virtual water contents of the crops under climate change are shown in Fig. 3, reported by Arefinia et al. (2021) (Fig. 4).

4 Results and discussion

A 40% available water usage (this is the United Nations threshold for severe water crisis) in each farm area was imposed as a constraint to maintain water security, while the total cereals production in the region to preserve the food security of the whole country considering population growth was imposed as a food security constraint. The optimization problem results in the 2030s, 2050s, 2070s, and 2090s under RCPs 2.6, 4.5, and 8.5 are displayed in Fig. 5.

Figure 5 depicts 12 Pareto fronts are plotted for the three RCPs over four study periods. Each Pareto front represents the combination of optimal values for the objective functions, which imply an optimal cropping pattern for its corresponding conditions. The range of values of the first objective function is 3.7 to 7.3 (× 10^6) cubic meters. The range of values

Table 1 Change in temperature (ΔT) and precipitation (ΔP) under climate change relative to a baseline period (1986–2005) in eastern Iran (data from Arefinia et al. 2021)

Period	ΔT (°C)			ΔP (mm)		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
2030s	1.11	1.21	1.50	19.56	12.03	26.29
2050s	1.45	1.81	2.30	17.00	– 0.51	30.65
2070s	1.39	1.91	3.31	16.54	23.61	4.98
2090s	1.39	2.26	4.31	19.01	0.68	– 1.14

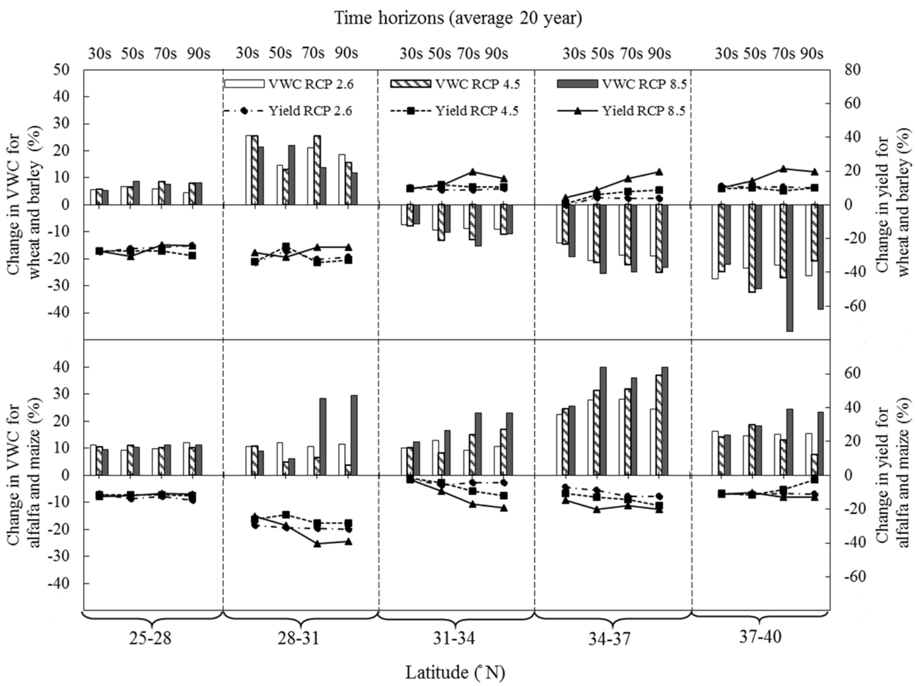

Fig. 3 Schematic of the results for the *VWC* and yield data under climate change conditions (data from Arefinia et al. 2021)

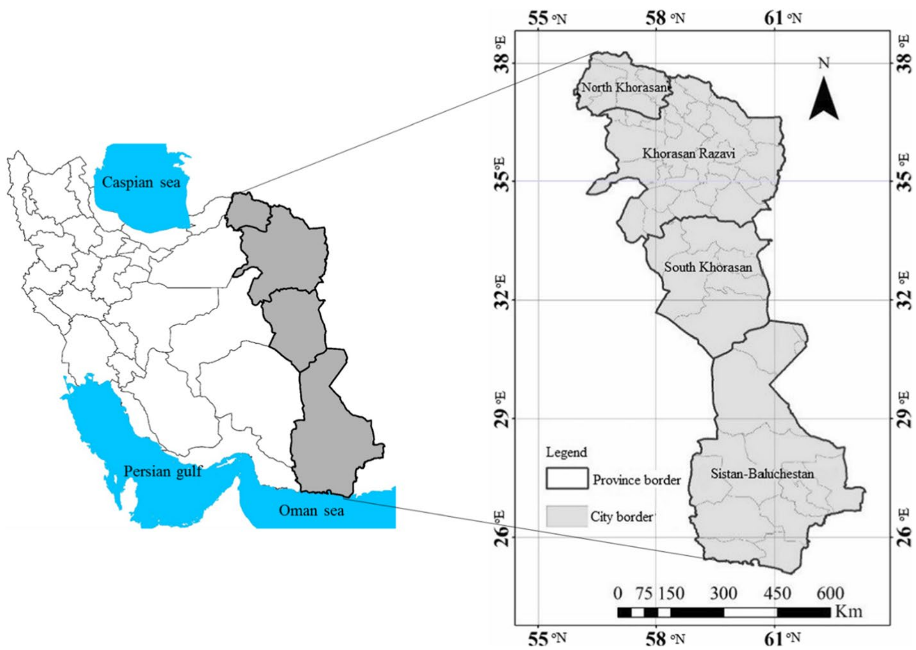

Fig. 4 Map of the study area

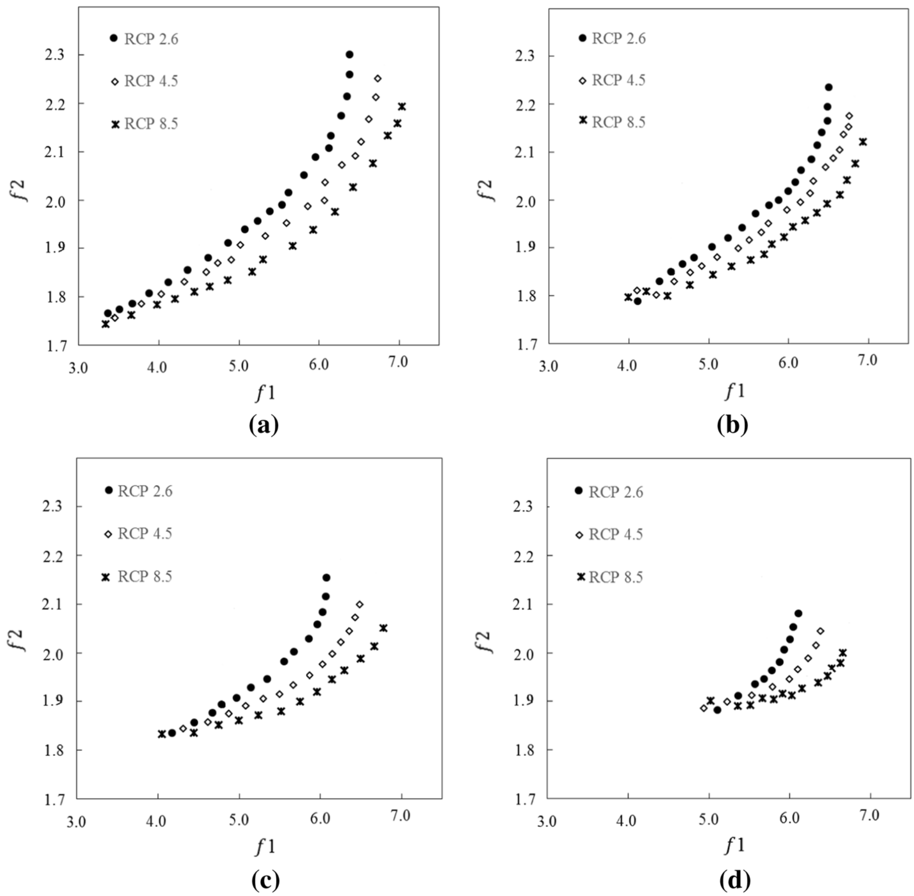

Fig. 5 Pareto fronts **a** 2030s, **b** 2050s, **c** 2070s, and **d** 2090s while considering water and food security constraints

of the second objective function is 1.73 to 2.32 billion Iranian Rials, which represents the range of virtual water content considering factors inherent to quality of life, employment, food production, available water levels, and population growth.

Figure 5 displays a comparison of RCPs 2.4, 4.5, and 8.5 shows that the maximum values of f_1 and f_2 have an increasing and decreasing trend (deterioration of the maximum response value), respectively. Increasing greenhouse gas emissions based on RCPs 2.4, 4.5, and 8.5 would raise the average temperature (Table 1), with a concomitant rise of the total virtual water use (based on Arefinia et al. 2021). Therefore, the maximum f_1 increases. On the other hand, reducing the total amount of crop yield (based on Arefinia et al. 2021) reduces the maximum value of f_2.

It is seen in Fig. 5 that the temporal trend of the objective functions from 2030 to 2090 based on the RCPs 2.6, 4.5, and 8.5 shows that, firstly, increasing population demand crop production (Table 2) means that the minimum values of f_1 and f_2 would increase. Second, given the downward trend in overall crop yield (based on Arefinia et al. 2021), the maximum value of f_2 based on all RCPs has a downward trend. However, the lack of trends in

Table 2 Estimated volume of products needed (million tons, 1 ton = 1000 kg)

Crops	Period				
	Baseline	2030s	2050s	2070s	2090s
Wheat	1.35	1.77	2.20	2.74	3.43
Barley	0.64	0.88	1.04	1.29	1.61
Alfalfa	0.61	0.88	0.99	1.24	1.55
Maize	0.98	1.29	1.60	1.99	2.49

average rainfall (Table 1) means that changes in the maximum f_1 values from the beginning of the 2030s to the end of the 2090s are constant with respect to all the RCPs.

The increase in population leads to a significant increase in demand for cereals as one approaches the end of the 2030s; it would be more than double the current amount by the end of the twenty-first century. Table 2 lists the estimated minimum production requirements for the products understudy in the 20-year 2030s, 2050s, 2070s, and 2090s intervals. It is seen in Table 2 that as the population grows, the need for crops increases. Nevertheless, the climatic projections in the study area indicate unsuitable conditions to meet the more significant level of production. Our results demonstrate that the achievable production in the 2050s, 2070s, and 2090s intervals equal 89%, 73%, and 48% of the crop demands, respectively.

5 Concluding remarks

Water and food shortages are a calamity affecting many arid and semi-arid countries, especially in middle-eastern countries. This study presents an approach to choosing cropping patterns considering the impacts of climate change on different water resources sectors, such as water and food security, using the concept of virtual water. The results demonstrate that the optimization model produces optimal cropping patterns under climate change conditions, summarized in 12 Pareto fronts for three RCPs in the future periods.

This work's results indicate that with the increase of greenhouse gas emissions based on the RCPS 2.6, 4.5, 8.5 the virtual water content would increase and the maximum farmers' income would decrease, auguring a deterioration of conditions over time. The warming surface temperature coupled with population growth was identified as a critical factor in this regard.

Population growth calls for larger future cereals production. However, future climatic projections in the study area indicate unsuitable conditions to support the more significant level of cereals production. Our analysis indicates that the achievable levels of crop production in the 2050s, 2070s, and 2090s, respectively, equal 89%, 73%, and 48% of the actual needs. Additional adaptive measures must be adapted to ensure food and water security in the study region.

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Author contributions OBH helped in conceptualization, supervision, project administration. AA and BZA contributed to software, formal analysis, writing—original draft. KA and HAL performed validation, writing–review & editing.

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Data availability The data supporting this study's findings are available from the corresponding author upon reasonable request.

Code availability The codes that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest There is no conflict of interest.

Consent for Publication All authors consent to publish.

Ethical approval All authors accept all ethical approvals.

Consent to Participate All authors consent to participate.

References

Adams RM, Rosenzweig C, Peart RM, Ritchie JT, McCarl BA, Glyer JD, Allen LH (1990) Global climate change and US agriculture. Nature 345(6272):219–224

Akbari-Alashti H, Bozorg Haddad O, Fallah-Mehdipour E, Marino MA (2014) Multi-reservoir real-time operation rules: a new genetic programming approach. In: Proceedings of the institution of civil engineers-water management (Vol. 167, No. 10, pp. 561–576). Thomas Telford Ltd

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration-guidelines for computing crop water requirements. FAO Irrig Drain 56:60–64

Arefinia A, Bozorg-Haddad O, Ahmadaali K, Bazrafshan J, Zolghadr-Asli B, Chu X (2021) Estimation of geographical variations in virtual water content and crop yield under climate change: comparison of three data mining approaches. Environ, Dev Sustain, 1–19

Arnell NW (2004) Climate change and global water resources: SRES emissions and socio-economic scenarios. Glob Environ Chang 14:31–52

Bozorg-Haddad O, Moradi-Jalal M, Mirmomeni M, Kholghi MK, Mariño MA (2009) Optimal cultivation rules in multi-crop irrigation areas. Irrig Drain: J Int Comm Irrig Drain 58(1):38–49

Davijani MH, Banihabib ME, Anvar AN, Hashemi SR (2016) Multiobjective optimization model for allocating water resources in arid regions based on the maximization of socio-economic efficiency. Water Resour Manage 30(3):927–946

Deb K (1999) Multiobjective genetic algorithms: problem difficulties and construction of test problem. Evol Comput 7(3):205–230

Deb K, Agrawl RB (1995) Simulated binary crossover for continuous search space. J Complex Systms 9(2):115–148

Deb K, Goyal M (1996) A combined genetic adaptive search (GeneAS) for engineering design. J Comput Sci Inform 26(4):30–45

Fallah-Mehdipour E, Bozorg-Haddad O, Rezapour Tabari MM, Mariño MA (2012) Extraction of decision alternative in construction management projects: application and adaptation of NSGA II and PSO. J Expert Syst Appl 36:2794–2803

FAO (1996) World food summit: rome declaration on world food security and world food summit plan of action. FAO

FAO (2015) Towards a water critical perspectives for policy-makers. Food and Agriculture Organization of the United Nations. Retrieved from http://www.fao.org/3/a-i4560e.pdf

FAO (2017) Water for sustainable food and agriculture: a report produced for the G20 presidency of Germany

FAO (2018) Transforming food and agriculture to achieve the SDGs. Retrieved from http://www.fao.org/family-farming/detail/en/c/11456210

Fischer G, Shah M, Tubiello NF, Van Velhuizen H (2005) Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080. Phil Trans R Soc B: Biol Sci 360(1463):2067–2083

Howden SM, Soussana JF, Tubiello FN, Chhetri N, Dunlop M, Meinke H (2007) Adapting agriculture to climate change. Proc Natl Acad Sci 104(50):19691–19696
Lawrence PR, Meigh J, Sullivan C (2002) The water poverty index: an international comparison. Department of Economics, Keele University, Keele, Staffordshire, UK
Misra AK (2014) Climate change and challenges of water and food security. Int J Sustain Built Environ 3(1):153–165
Oliazadeh A, Bozorg-Haddad O, Mani M, Chu X (2021) Developing an urban runoff management model by using satellite precipitation datasets to allocate low impact development systems under climate change conditions. Theoret Appl Climatol 146(1):675–687
Parry ML, Rosenzweig C (1990) Climate change and agriculture. Earthscan
Piao S, Ciais P, Huang Y, Shen Z, Peng S, Li J, Zhou L, Liu H, Ma Y, Ding Y (2010) The impacts of climate change on water resources and agriculture in China. Nature 467:43–51
Sarzaeim P, Bozorg-Haddad O, Fallah-Mehdipour E, Loáiciga HA (2017) Discussion of "Multiobjective Management of Water Allocation to Sustainable Irrigation Planning and Optimal Cropping Pattern" by R. Lalehzari, S. Boroomand Nasab, H. Moazed, and A. Haghighi. J Irrig Drain Eng 143(4):07016023
Singh A (2012) An overview of the optimization modeling applications. J Hydrol 466:167–182
Su XL, Li JF, Singh VP (2014) Optimal allocation of agricultural water resources based on virtual water subdivision in the Shiyang River Basin. Water Resour Manag 28(8):2243–2257
USGCRP, (2017). Climate Science Special Report: Fourth National Climate Assessment, Volume 1. Washington, D.C., USA
USGS (2016) How Much Water is there on, in, and above the earth? U.S. Department of the Interior. U.S. Geological Survey, Washington, D.C.
Wilby RL, Dawson CW, Barrow EM (2002) SDSM is a decision support tool for assessing regional climate change impacts. Environ Model Softw 17(2):145–157
World Bank Group (2016) Annual freshwater withdrawals, agriculture (% of total freshwater withdrawal). The World Bank Group, Washington, D.C. Available at ⟨https://data.worldbank.org/indicator/er.h2o.fwag.zs⟩ (Accessed on October 26, 2018)
Ye Q, Li Y, Zhuo L, Zhang W, Xiong W, Wang C, Wang P (2018) Optimal allocation of physical water resources integrated with virtual water trade in water-scarce regions: a case study for Beijing, China. Water Res 129:264–276

Authors and Affiliations

Ali Arefinia[1] · Omid Bozorg-Haddad[1] · Khaled Ahmadaali[2] · Babak Zolghadr-Asli[3,4] · Hugo A. Loáiciga[5]

Ali Arefinia
Ali.Arefinia@ut.ac.ir

Khaled Ahmadaali
khahmadauli@alumni.ut.ac.ir

Babak Zolghadr-Asli
Zolghadrbabak@ut.ac.ir

Hugo A. Loáiciga
HLoaiciga@ucsb.edu

1 Department of Irrigation & Reclamation Engineering, Faculty of Agriculture Engineering & Technology, College of Agriculture & Natural Resources, University of Tehran, Karaj, Alborz, Iran

2 Department of Arid and Mountainous Regions Reclamation, Faculty of Natural Resource, University of Tehran, Tehran, Iran

3 Centre for Water in the Minerals Industry, Sustainable Minerals Institute, The University

of Queensland, Brisbane, Australia

[4] The Centre for Water Systems (CWS), The University of Exeter, Exeter, UK

[5] Department of Geography, University of California, Santa Barbara, CA 93106, USA