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Optimal cropping patterns using linear programming and evaluation based on food-energy-water nexus

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ABSTRACT

BACKGROUND AND OBJECTIVES: Agriculture plays a significant role in the overall consumption of freshwater resources, accounting for approximately 70 percent of the total use. Energy is also essential at various stages of agriculture and the food chain. On a global scale, the agricultural and food industries account for approximately 30 percent of the overall energy consumption, with a significant portion derived from fossil fuel sources. This underscores the intricate interconnection between food, energy, and water resources. This study utilizes a linear programming model to determine the optimal cropping pattern while minimizing water usage in agriculture. This study's primary contribution lies in its dual approach: it identifies the optimal cropping patterns for a specified objective function through linear programming while simultaneously conducting a comprehensive analysis of these patterns by integrating considerations of food, energy, and water nexus.

METHODS: The constraints applied in linear programming involve maintaining nearly the same agricultural revenue, conserving the total cultivation area, and limiting the change intervals in cultivation area by 5 percent. Using linear programming, crop patterns were determined for the periods of 2017, 2025-2050, 2050-2075, and 2075-2100. In each scenario, calculations were conducted to assess water consumption, energy demands, agricultural income, and carbon dioxide emissions, all framed within the context of the food-energy-water nexus. The various scenarios were subsequently analyzed to assess their effects. An evaluation was conducted regarding the sustainability of water usage in agricultural production.

FINDINGS: All the scenarios examined resulted in lower water usage, reduced energy requirements, and decreased carbon dioxide emissions. Throughout various time periods, scenario 6, which permits a 5 percent variation in cultivation areas without imposing a total cultivation area limit, consistently proved to be the most favorable choice. It achieved an average reduction of 3.94 percent in water usage, 2.95 percent in energy requirements, and 1.62 percent in carbon dioxide emissions compared to the base scenario. Scenario 11, allowing for a 5 percent variation in cultivation areas while maintaining a total cultivation area limit, was evaluated as the second most effective scenario in terms of water conservation. It achieved an average reduction in water use of 3.45 percent, an average reduction in energy requirements of 1.85 percent, and a minimal reduction in carbon dioxide emissions of 0.11 percent across all time periods.

CONCLUSION: The outcomes of this study reveal that the proposed model can play a crucial role in advancing sustainable agricultural management strategies. The obtained results indicate that significant reductions in water usage, energy requirements, and carbon dioxide emissions can be achieved simply by modifying the crop pattern, while agricultural income remains largely at the same level. The imposition of a constraint requiring the total cultivation area to be equal to or greater than that of the baseline scenario in the linear programming model has been found to restrict the extent of these reductions.

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INTRODUCTION

The interconnections among the systems of water, energy, and food are significant. Water plays a crucial role in the production of energy, whereas energy is vital for the processes of accessing, treating, and distributing water resources. Both energy and water play crucial roles in agriculture and raising livestock. Understanding this interrelationship is crucial, as a malfunction in one system has the potential to affect the functioning of the others. Understanding the intricate and ever-changing relationships among water, energy, and food is crucial for effectively managing these limited resources sustainably. The Sustainable Development Goals for 2030, established by the United Nations in 2015, place significant emphasis on ensuring food and water security, delineating a total of 17 objectives aimed at promoting sustainable development. Goal 2 focuses on eliminating hunger, ensuring food security, achieving adequate nutrition, and promoting sustainable agriculture. Goal 6 aims to ensure the availability of clean water and sanitation for all, alongside sustainable management of water resources (United Nations, 2015). Agriculture stands as the foremost user of the Earth's freshwater reserves, constituting roughly 70 percent (%) of the world's freshwater withdrawals and utilizing about 30% of global energy (FAO, 2011). The agricultural production sector is widely recognized for its significant consumption of water resources. The complex relationships between water, food, and energy highlight concerns associated with this sector. The optimal cultivating pattern for a specific land area to restrict water use to a certain level is one of the most important topics for sustainability of water in agricultural production. The implementation of effective optimization strategies for crop area planning is essential and beneficial for the managing agricultural water resources. They facilitate the allocation of water to different crop areas, ensuring the achievement of sustainability objectives (Zeng *et al.,* 2010). Linear programming (LP) serves as a widely utilized technique for determining the most efficient crop arrangement within a given agricultural landscape. Various researchers have utilized LP models to determine the optimal cropping patterns based on the existing resources and constraints. Singh *et al.* (2001) estimated the irrigation water needs for main crops and the total water available from both canal and groundwater sources within the Shahi Distributory command area. A linear programming model was developed to identify the optimal cropping pattern that maximizes net profit under different levels of water availability. Wheat emerged as the most consistently profitable crop in this area. Georgiou and Papamichail (2008) created a non-linear programming model incorporating an integrated soil water balance. This model establishes the most effective reservoir discharge rates, distributes irrigation resources among different crops, and determines the ideal crop arrangement for agricultural output. Bhuvandas *et al.* (2010) introduced a LP model to optimize crop area allocation within the Ukai reservoir command area. The objective is to optimize the overall relative yields of all crops cultivated in the irrigated area, taking into account different levels of water availability. Gadge *et al.* (2014) created a LP model that considered the available water resources and proposed a diverse cropping pattern aimed at maximizing profits. The newly developed methodology was subsequently evaluated against the current cropping pattern. Osama *et al.* (2017) developed a linear optimization model aimed at maximizing the yearly net return in Egypt's three old regions. The analysis encompasses data from 28 crops spanning five years, from 2008 to 2012. The model incorporates regional differences in agricultural practices, including variations in crop types, irrigation needs, crop productivity, and food consumption patterns. In the study, crop types are divided into two categories: non-strategic and strategic crops. The model takes into account the regional disparities in agricultural methodologies, which encompass differences in crop varieties, irrigation requirements, levels of crop yield, and patterns of food consumption. Crops like tomatoes, which yield higher net returns, have observed a considerable increase in their allocated land. Daghighi *et al.* (2017) used LP to create a water resource planning model aiding decision-makers in selecting an optimal crop arrangement, maximizing surface water utilization, and effectively distributing water among various crops to mitigate water scarcity's adverse impacts. Over a five-year span, the model was utilized to account for gradual changes, identifying the most suitable water usage pattern from the available resources. Findings indicate a potential for gradual enhancement in rectifying the negative water balance to eventually achieve positive. Imron and Murtiningrum (2021) aimed to achieve optimal

cropping areas and maximize benefits through the optimized allocation of irrigation water, considering dependable discharge and existing land area. The researchers investigated a range of cropping patterns to identify the most effective crop area by employing linear programming for the allocation of irrigation water. Kumar *et al.* (2022) employed a LP model to suggest cropping patterns, taking into account the rotational policy of the Bhadra reservoir canal system. The model integrates various constraints, including the availability of water and land, the decisions made by farmers, and the suitability of soil, to derive a cropping pattern that seeks to optimize net benefits. The food-energy-water (FEW) nexus is recognized as a practical concept used to describe the interconnected nature of global resource systems. The nexus approach provides a comprehensive analysis of the interconnections between human activities and environmental factors, facilitating the integrated management of natural resources across multiple sectors and levels (FAO, 2014). Especially in recent years, this approach has gained importance due to the consideration of preserving fundamental natural resources and climate variability. The use of the FEW nexus approach, addressing issues related to resources in water, energy, and food systems, gained momentum in the late 2000s. Considered as a globally significant international event that increased attention to the nexus approach, the "Bonn 2011 Nexus Conference: The Water-Energy and Food Security Nexus – Solutions for a Green Economy," marked the first major FEW nexus gathering. This conference involved the participation of various major groups, including the private sector, and is recognized for boosting awareness of the nexus approach on a global scale (Leck *et al.,* 2015). The Bonn 2011 Nexus Conference (Hoff, 2011) provided guidance toward understanding nexus interactions. El-Gafy *et al.* (2017) performed a comparative analysis of nexus and non-nexus methodologies to develop an optimal cropping pattern that incorporates water, energy, and economic dimensions. Their assessment of linear optimization techniques revealed that the nexus approach, which integrates considerations of water, food, and energy, provides a holistic framework for determining cropping patterns that reduce water and energy consumption while enhancing agricultural net returns. Chen *et al.* (2018) constructed a multi-region input-output model to analyze the global land-water nexus. The study concentrated on monitoring the worldwide patterns of agricultural land utilization and freshwater usage, in addition to examining the productivity of land and the water needs associated with various crops. Tian *et al.* (2018) systematically improved resource use efficiencies within the FEW nexuses to promote sustainable agriculture. They employed a conceptual model within a decision support system, underscoring the importance of integrated management across agricultural systems. Li *et al.* (2019) developed an optimization framework designed to allocate resources effectively for the sustainable management of the agricultural FEW nexus, especially in the face of uncertain conditions. Their model enables policymakers to identify optimal policy options regarding water, energy, and land resources to achieve maximum economic return while minimizing environmental impacts. Yuan and Lo (2020) introduced a systematic approach aimed at developing an extensive array of interconnected indicators pertinent to each sector within the FEW nexus. These indicators enable the analysis of specific issues and the formulation of region specific and national solutions. Abdi *et al.* (2020) conducted a comprehensive review of recent research on FEW nexus. In pursuit of this objective, considerable attention was directed towards the available statistics, accompanied by an examination of key studies that have emerged in this domain, particularly given that nearly ten years have elapsed since the initial concept was introduced. The discussion included actions policymakers need to take according to the nexus approach, along with important challenges and opportunities for implementation, concluding with future projections. Saray *et al.* (2022) conducted a study aiming to evaluate the water-energy-food nexus and carbon dioxide (CO_2) emissions in a farm situated in Northwest Iran. The study analyzed six essential indicators, which encompassed the energy input-output ratios for seven different crop varieties, as well as assessments of water and energy usage, productivity levels, and economic efficiency. The water-energy-food nexus index, derived from these indicators, demonstrated that silage corn had the highest value, indicating its superior performance, while potato showed the lowest value. Optimization assessments highlighted barley, rapeseed, silage corn, and wheat as the most successful crops under the study's conditions. The study conducted by Kamyab *et*

al. (2023) focused on the application of cutting-edge technologies, such as artificial intelligence and big data analytics, to mitigate the challenges inherent in data acquisition that are typically encountered with traditional water resource management practices.. They also outlined forward-looking directions for utilizing these methods to achieve optimal water resource allocation. A review of the existing literature reveals that significant research efforts have been directed towards the optimization of agricultural production as well as FEW nexus framework. Most optimization studies using LP method focus on maximizing annual net profit and optimally allocating water or land among various crops. Given that agricultural water usage constitutes a significant portion of overall water consumption, there exists a notable lack of research focused on minimizing the water footprint associated with this sector. This study aims to fill the existing gap by identifying the most appropriate cropping patterns, with a primary focus on minimizing water consumption as the objective function. Additionally, it intends to evaluate the effects of these cropping patterns on various factors, including energy demand, agricultural income, and CO_2 emissions, utilizing the FEW nexus framework. The main novelty of this study is the integration of FEW nexus based assessment into the determination of optimal crop patterns. In this study, the LP model was used to identify optimal cropping patterns that minimize agricultural water consumption. Then, using the cropping patterns obtained with LP, water usage, energy consumption, agricultural revenue and CO_2 emission parameters were calculated under different scenarios based on the FEW nexus and the scenarios were evaluated comparatively. This study seeks to explore the possible water conservation outcomes that may be realized through various scenarios in agricultural production. This study aims to optimize the distribution of irrigation water based on the available water supply, enhancing agricultural revenue by considering constraints related to crop area, cropping patterns, and water needs. The study has been carried out in Istanbul region of Turkey in 2024.

MATERIALS AND METHODS

The core techniques applied in this study consist of LP and the FEW nexus model. In this section, the LP method, selected as the most suitable option for determining optimal cropping patterns based on a specific objective function within certain constraints, is explained in detail along with the FEW nexus approach. The study area is also characterized by the presentation of geographical information and data pertaining to agricultural production.

Linear programming

Linear programming stands as a pivotal advancement in recent history, offering problem-solving capabilities across various disciplines (Simonovic, 1992). The concept of linear programming (LP) was first introduced by George Dantzig in 1947, along with the Simplex algorithm, which is extensively utilized for solving linear problems. In linear programming, it is crucial that both the objective function and the constraints maintain a linear form (Dantzig, 1963). While, real-life scenarios often present nonlinear complexities, linear models serve as effective approximations. Despite this, LP offers several notable advantages, including its efficiency in handling large-scale problems, the capability to converge to global optima, and a well-established duality theory beneficial for sensitivity analysis (Labadie, 2004). Typically, these models allow for an easy implementation process for users and can be effectively solved using current linear programming solvers, thus obviating the need for initial solutions provided by the user. Thanks to computer programs capable of solving LP problems, LP has become widely regarded as one of the most utilized optimization algorithms across various practical applications. It serves to assess and appraise alternative strategies, designs, and administrative approaches in agriculture, business, commerce, education, engineering, finance, government sectors (civil and military), and numerous other domains. When both the objective function, which consists of decision variables, and all constraints are linear, the model is identified as a LP model. The typical format of a LP model follows the structure given in Eqs. 1 to 3 (Loucks and van Beek, 2017).

$$Maximize\,or\,minimize\,Z = \sum_j c_j x_j \quad (1)$$

Subject to the restrictions,

$$\sum_j a_{ij} x_j \le or \ge b_i \; for\, i = 1,2,3,\ldots,m \quad (2)$$

And

$$x_j \geq 0 \quad for\ j = 1,2,3,\ldots,n \tag{3}$$

The fundamental terminology used in a LP model can be encapsulated through the following explanations. The function that undergoes maximization or minimization, expressed as $c_1x_1 + c_2x_2 + \cdots + c_nx_n$, is named as the objective function. Correspondingly, the restrictions concerning non-negativity are referred to as non-negativity constraints (or non-negativity conditions) (Hillier and Lieberman, 2010). If a model adheres to this general structure, numerous LP software tools are available to determine the "optimal" values for all the unknown decision variables x_j. The majority of commercial LP software integrates non-negativity constraints into their solution algorithms, thereby eliminating the need to explicitly specify these conditions for each individual applications (Loucks and van Beek, 2017). The LP model used in this study was developed to obtain the optimal cropping pattern that minimizes water use in agricultural production. An essential limitation within the model asserts that the agricultural revenue attained must be no less than the existing revenue obtained from the available dataset. Another constraint is the addition of upper and lower limits to prevent too large or too small changes in the planting areas allocated for agricultural crop types to meet food demand adequately. The current study explored two separate conditions: the enforcement of the constraint that requires the total area under cultivation to be equal to or greater than the available total cultivation area, and the scenario in which this constraint is disregarded.

Food, energy, water nexus

The term "nexus" broadly describes a system in which interconnected elements interact through feedback loops, necessitating the analysis of these elements together to comprehend their interdependencies (Caputo *et al.,* 2021). This idea highlights the fact that these elements are not independent entities; instead, they are closely interconnected, suggesting that changes in one element can significantly impact the others (Ansari *et al.,* 2023). The water-food-energy nexus was argued by Kurian (2017) to rely on robust scientific foundations, with the challenges associated with this approach highlighted, including concepts like synergies, trade-offs, and optimizing resource use. Water, energy, and food represent three interrelated resources, and the decision-making processes concerning these resources require a thorough analysis of the trade-offs involved. Water is an essential component in the production of agricultural goods. Energy is also required for various agricultural operations, including the use of tractors and farm tools, transportation of agricultural products, pumping groundwater, and conveying surface water, among other field-related processes. A lack of resources or their overexploitation can cause disruptions in other areas, which may jeopardize their stability and functionality. Maintaining a balance among these resources is crucial to ensure their security (Mohtar and Daher, 2012). Understanding the interdependency among these resources requires quantifying their connections through data-centric and quantitative modeling approaches (Degirmencioglu *et al.,* 2019). The application of modeling techniques centered on the WEF nexus can enhance the consistency of decision-making processes aimed at developing sustainable resource allocation strategies. In earlier studies, the WEF Nexus Tool 2.0 was established as a collaborative platform for the assessment of various scenarios, with the objective of determining effective strategies for sustainable resource allocation. This tool enables the creation of diverse scenarios dependent on different conditions of water, energy, and food resources. While resource analyses generate outputs in terms of national-level resource requirements, consumptions, and carbon emissions, creating scenarios at a regional or watershed level is necessary to obtain specific interactions among resources in that particular region (Mohtar and Daher, 2014). Through basin-specific research, optimal crop pattern scenarios are developed that enhance water security for the crops cultivated within the basin, allowing for the calculation of outputs associated with each scenario. These can be listed as water use, energy use, CO_2 emission, agricultural revenue. For this purpose, each scenario is determined by taking into account the changes that can be seen in the agricultural crop pattern depending on water requirements and spreadsheets are created for these scenarios. The need for water is a consequence of agricultural crop production, with each agricultural crop type requiring a specific amount of irrigation water. The total

water required to cultivate agricultural crops in the watershed can be met from various sources such as surface and groundwater. The volume of water used in livestock production is aggregated with the water necessary for the growth of agricultural crops, thereby facilitating the calculation of the comprehensive water requirements for agriculture. The average daily water requirement per animal is taken into account for both large and small livestock regarding their water consumption. The total agricultural water consumption is obtained by summing up the water needs for crops and livestock, using Eqs. 4 to 6 (Kulat *et al.,* 2019).

$$W_c = \sum_i W_{c_i} \; L_i \tag{4}$$

$$W_l = \sum_i W_{l_i} \; N_i .365 \tag{5}$$

$$W_T = W_c + W_l \tag{6}$$

Where, L_i is the land allocated for the specific crop, W_c is the total need for all crops for irrigation, N_i is the number of large and small livestock, W_l is the total livestock water requirements annually and W_T is the total agricultural water requirement.

Within the watershed, the energy demand is crucial for diverse farming operations that occur during the production phase in the fields, in addition to facilitating water supply from various sources. Energy requirements related to the use of surface or groundwater for irrigation are calculated based on the energy footprint values for each source type. Energy demands in agricultural practices encompass a range of activities, including soil preparation, planting, cultivation, harvesting, fertilization, and various other agricultural operations. The assessment of energy requirements is performed individually for each type of agricultural crop. The overall energy demand for agricultural operations is derived from the cumulative energy needs of all crops within the region, which is determined by analyzing fuel consumption across all stages of production, from soil preparation to harvesting, for each specific. The fuel consumption required for each agricultural crop type throughout these processes, multiplied with the cultivated area, is used to calculate energy requirements. The total energy requirement is obtained by summing the requirement for water conveyance and farming operations, using Eqs. 7 to 9 (Kulat *et al.,* 2019).

$$E_T = E_{\mathrm{sw}} + E_{\mathrm{gw}} + E_{\mathrm{fo}} \tag{7}$$

$$E_{sw} = \alpha_{sw} \times V_{sw} \tag{8}$$

$$E_{gw} = \alpha_{gw} \times V_{gw} \tag{9}$$

Where, E_T is total energy requirement, E_{sw} is the energy need for conveyance of surface water, E_{gw} is the energy need for pumping of groundwater and E_{fo} is the energy need for farming operations. α is the energy needed for unit volume of water and V is the volume of water used for irrigation depending on water type.

CO_2 emissions are used as another parameter to evaluate the sustainability of a scenario. CO_2 emissions primarily result from energy consumption. The scenario presents different energy types, each characterized by distinct coefficients that denote the CO_2 emissions generated, expressed in tons for every unit of energy utilized. CO_2 emissions for each type of energy consumption is evaluated separately and then aggregated, using Eq. 10 (Degirmencioglu *et al.,* 2019).

$$CO_2 = \sum_i E_i \, \Delta_i \tag{10}$$

Where, E represents the various types of energy consumption and Δ represents tons of CO_2 per unit energy consumption.

Agricultural revenue is considered as a key parameter for financial assessment of each scenario. Total agricultural revenue can be calculated by using the total production values and unit market prices for each agricultural product, using Eq. 11 (Degirmencioglu *et al.,* 2019).

$$\mathrm{R} = \sum_i P_i U_i \tag{11}$$

Where, R is the total agricultural revenue, P is the agricultural production and U is the unit market price for each agricultural product. The methodology used in this study is summarized in Fig. 1.

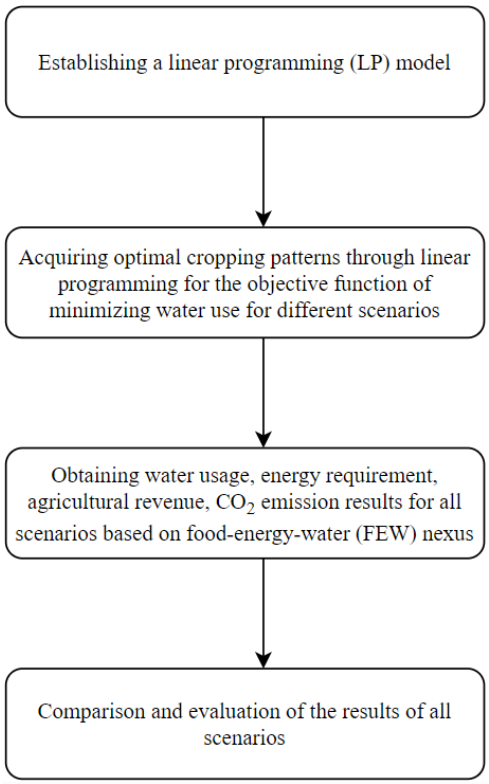


Fig. 1: Methodology of the study

Study area

The Gediz Basin is located in the western region of Turkey, specifically within the Aegean Region. It encompasses the territory that channels its waters into the Aegean Sea via the Gediz River and its associated tributaries, including the areas bordered by the Northern Aegean, Susurluk, and Küçük Menderes Basins. The location of Gediz Basin is shown in Fig. 2. The Gediz Basin covers an approximate area of 17,140 square kilometers (km²), constituting 2.2% of Turkey's total land area. The Gediz River, after which the basin is named, is approximately 275 kilometers (km) long and serves as the largest water source in the basin. Of the Gediz River, 175 km is situated in the province of Manisa, 40 km in Kütahya, 25 km in Uşak, and 35 km in İzmir. The annual average water potential is calculated to be 2.8 million cubic meters (m³), with an average precipitation of 584 milimeters (mm). The total agricultural land area in the basin is approximately 1,774 km² (SYGM, 2019).

When examining the precipitation data of the basin, it is observed that the annual average precipitation values are higher around the Kemalpaşa and Demirci stations; in the northern parts of the basin, these values are lower compared to the vicinity of these two stations, and in the southern parts, they are observed to be the lowest. In the basin, the peak average monthly precipitation is recorded in the months of December and January, whereas the months of July and August experience the least average precipitation (SYGM, 2019). An analysis of temperature data across the basin reveals that the peak average monthly temperatures occur during the months of July and August, whereas the lowest average temperatures are noted in January. Agricultural production data for the six crop types used in the study were sourced from a report specifically prepared for the basin by the General Directorate of Water Management (SYGM). The data served as a foundational scenario for the development of various alternative scenarios, which were contingent upon the applied constraints. The outcomes related to water consumption, energy



Fig. 2: Geographic location of the study area in Gediz Basin, Turkey

demands, and CO_2 emissions derived from this data were utilized as benchmarks for comparative analysis. The agricultural production data for the year 2017 obtained from the Gediz Basin Drought Report prepared by SYGM, along with annual production projections for future periods, are presented in Table 1 below (SYGM, 2019).

For each crop, fertilizer requirements, seasonal water needs, irrigation requirements, and fuel consumption based on tractor use in agricultural activities are shown in Table 2 in units of kilograms per hectare (kg/ha), cubic meters per hectare (m^3/ha), and liters per hectare (L/ha) (TurkStat, 2014).

Fuel consumption stands out as the most essential energy input in agricultural production processes, which is consistent with the observation that diesel is the main energy source utilized in Turkey's agricultural sector. The energy requirement varies according to the type of water source used. The energy requirements per unit volume of water are 0.4068 kilowatt hours per cubic meters (kWh/m^3) and 0.209 kWh/m^3 for groundwater and surface water (Degirmencioglu *et al.,* 2019). The emission of CO_2 is 0.00268 tons per liter from diesel use and 0.0026 tons per kilogram from the use of nitrogen, phosphorus and potassium fertilizers in agricultural production processes. (Wood and Cowie, 2004).

RESULTS AND DISCUSSION

In the context of this study, the LP method was

Table 1: The agricultural production data for the year 2017 and future period production projections

Planted crop	Production(tonnes) (2017)	Production(tonnes) (2025-2050)	Production(tonnes) (2050-2075)	Production(tonnes) (2075-2100)
Tomato	916950	1377834	2059207	2733990
Wheat	257807	291761	305572	350489
Corn	251641	325543	457944	621618
Grape	1098109	1368957	1836569	2307080
Cherry	108028	143965	206602	269594
Olive	206932	260526	341855	427850

Table 2: Various requirements and fuel consumption values for agricultural products

Planted crops	Nitrogen requirement (kg/ha)	Phosphorus requirement (kg/ha)	Potassium requirement (kg/ha)	Seasonal water requirement (m^3/ha)	Irrigation requirement (m^3/ha)	Gasoline consumption (L/ha)
Tomato	136,1	73,1	37,7	4028,5	2849,5	180,46
Wheat	120	40	0	4836,1	1182,9	65,6
Corn	272,7	166,6	0	2530	1794,9	159,1
Grape	55,8	51,5	41,6	6584,5	5396	225,55
Cherry	187,5	180,2	166,1	2094,4	1084,5	267,93
Olive	90	72	55,4	8928,4	0	50,93

applied to establish the ideal cropping patterns for the purpose of minimizing water use in agricultural practices. For the time periods 2017, 2025-2050, 2050-2075 2075-2100, the existing production and projection data for the basin were taken as the base or reference scenario. Subsequently, calculations pertaining to water consumption, energy demands, agricultural revenue, and CO_2 emissions for these time frames have been derived from data associated with the baseline scenario, utilizing the framework of the FEW nexus. Alongside the base scenario, changes in cropping patterns were evaluated as scenarios. In the derivation of these scenarios, LP was utilized to obtain optimal cultivation areas with the objective function of minimizing water usage, and constraints were set to be equal to or higher than the agricultural income amount in the base scenario, and allowing spatial changes in the cultivation areas within the ranges of 1%, 2%, 3%, 4%, and 5%. The implementation of upper and lower limits on the acreage designated for each crop serves to mitigate excessive fluctuations in land allocation, ensuring that changes remain within a manageable range while simultaneously addressing food demand. In crop pattern change scenarios where a total cultivation area constraint is also applied, LP was again used with the objective function of minimizing water usage, and constraints were set to be equal to or higher than the agricultural income amount in the base scenario, having the total cultivation area equal to or larger than that in the base scenario, and allowing spatial changes in the cultivation areas within the ranges of 1%, 2%, 3%, 4%, and 5%. By analyzing these two individual cases, the study seeks to enhance our understanding of how the existence or non-existence of a total cultivation area constraint influences the parameters generated within the FEW nexus framework. In naming the examined scenarios, the available data is taken as base or reference scenario for comparisons and denoted as Scenario 1. In LP, scenarios 2, 3, 4, 5, and 6 represent cases where there are no constraints on the total cultivation area, and spatial changes in cultivation areas for each crop are within the intervals of 1%, 2%, 3%, 4%, and 5%. Scenarios 7 through 11 represent instances in which a limitation is imposed on the overall cultivation area, taking into account spatial variations in cultivation zones within the ranges of 1%, 2%, 3%, 4%, and 5%. The cultivation area values obtained for the optimal crop pattern that minimizes water consumption using the LP method for each period are shown in hectares (ha) in Tables 3, 4, 5, and 6.

After obtaining different crop pattern scenarios with LP, water usage, energy requirement, agricultural revenue, and CO_2 emissions were calculated for these scenarios based on FEW nexus and compared for each scenario in the periods 2017, 2025-2050, 2050-2075, and 2075-2100. The findings derived from the

Table 3: The crop pattern obtained through LP for the year 2017

Cultivation Area (ha)	Tomato	Wheat	Corn	Grape	Cherry	Olive
Scenario 1	13354,4	93885,3	24534,9	61397,8	18806,4	93297
Scenario 2	13487,9	92945,7	24290,6	60784,3	18837,8	94229,6
Scenario 3	13621,4	92006,9	24045,3	60170,4	18820,9	95162,6
Scenario 4	13755	91068	23799,9	59556,4	18804,1	96095,6
Scenario 5	13888,5	90129,2	23554,5	58942,4	18787,2	97028,5
Scenario 6	14022,1	89190,3	23309,2	58328,4	18770,3	97961,5
Scenario 7	13417,8	93558,2	24290,6	60784,3	18995,2	94229,6
Scenario 8	13465,6	93248,7	24045,3	60170,4	19183,3	95162,6
Scenario 9	13513,4	92939,2	23799,9	59556,4	19371,3	96095,6
Scenario 10	13561,2	92629,7	23554,5	58942,4	19559,4	97028,5
Scenario 11	13609	92320,2	23309,2	58328,4	19747,5	97961,5

Table 4: The crop pattern obtained through LP for the period 2025-2050

Cultivation Area (ha)	Tomato	Wheat	Corn	Grape	Cherry	Olive
Scenario 1	20066,7	106250,3	31740,3	76541,5	25062,6	117460,3
Scenario 2	20267,3	105187	31424,3	75776,8	24979,9	118634,5
Scenario 3	20467,9	104124,5	31106,9	75011,3	24837,9	119809,1
Scenario 4	20668,6	103062	30789,5	74245,9	24695,8	120983,7
Scenario 5	20869,3	101999,5	30472	73480,5	24553,8	122158,3
Scenario 6	21069,9	100937	30154,6	72715,1	24411,8	123332,9
Scenario 7	20140,1	105831,9	31424,3	75776,8	25314,2	118634,5
Scenario 8	20194,4	105435,2	31106,9	75011,3	25564,8	119809,1
Scenario 9	20248,8	105038,5	30789,5	74245,9	25815,5	120983,7
Scenario 10	20303,1	104641,7	30472	73480,5	26066,1	122158,3
Scenario 11	20357,4	104245	30154,6	72715,1	26316,7	123332,9

Table 5: The crop pattern obtained through LP for the period 2050-2075

Cultivation Area (ha)	Tomato	Wheat	Corn	Grape	Cherry	Olive
Scenario 1	29990,2	111279,8	44649,4	102686,8	35967	154128,1
Scenario 2	30290	110166,2	44204,8	101660,8	35751,4	155668,9
Scenario 3	30589,9	109053,4	43758,3	100633,9	35454,1	157210,1
Scenario 4	30889,8	107940,6	43311,8	99607	35156,8	158751,4
Scenario 5	31189,7	106827,8	42865,3	98580,2	34859,5	160292,7
Scenario 6	31489,6	105715	42418,8	97553,3	34562,2	161834
Scenario 7	30088,1	110750,6	44204,8	101660,8	36328	155668,9
Scenario 8	30159,8	110251,4	43758,3	100633,9	36687,7	157210,1
Scenario 9	30231,4	109752,2	43311,8	99607	37047,4	158751,4
Scenario 10	30303,1	109253	42865,3	98580,2	37407,1	160292,7
Scenario 11	30374,8	108753,7	42418,8	97553,3	37766,7	161834

scenarios for the year 2017, along with a comparative analysis of these results, are presented in Fig. 3.

Comparing the results of the scenarios for the year 2017, the largest decrease in water usage, with a decrease of 23.4 million m^3 and a proportional decrease of 4.02% compared to the base scenario, occurred in scenario 6, which allows a 5% change in cultivation areas without a total cultivation area constraint, and in scenario 11, which allows a 5% change in cultivation areas with a total cultivation area constraint, where there was a decrease of 19.8 million m^3 and a proportional decrease of 3.4% compared to the base scenario. The analysis revealed that scenario 6 had the largest decline in energy requirements, with a reduction of 2.83%. This was closely followed by scenario 5 with a decrease of 2.26%. Agricultural revenue was almost equal in all scenarios. A decrease in CO_2 emissions occurred in all scenarios, with the highest decrease of 1.38% in scenario 6 and 1.1% in scenario 5. The findings derived from the scenarios analyzed for the years 2025 to 2050, along with a comparative assessment

Table 6: The crop pattern obtained through LP for the period 2075-2100

Cultivation Area (ha)	Tomato	Wheat	Corn	Grape	Cherry	Olive
Scenario 1	39817,7	127637,2	60607,5	128994,1	46933,1	192899,7
Scenario 2	40215,7	126359,8	60004,1	127705,3	46603,2	194828
Scenario 3	40613,9	125083,5	59398	126415,3	46167,5	196757
Scenario 4	41012	123807,1	58791,9	125125,4	45731,7	198686
Scenario 5	41410,2	122530,8	58185,8	123835,4	45295,9	200615
Scenario 6	41808,4	121254,4	57579,7	122545,5	44860,2	202544
Scenario 7	39940,7	127007	60004,1	127705,3	47404,3	194828
Scenario 8	40029,8	126415,6	59398	126415,3	47873,6	196757
Scenario 9	40118,9	125824,3	58791,9	125125,4	48342,9	198686
Scenario 10	40207,9	125232,9	58185,8	123835,4	48812,3	200615
Scenario 11	40297	124641,6	57579,7	122545,5	49281,6	202544

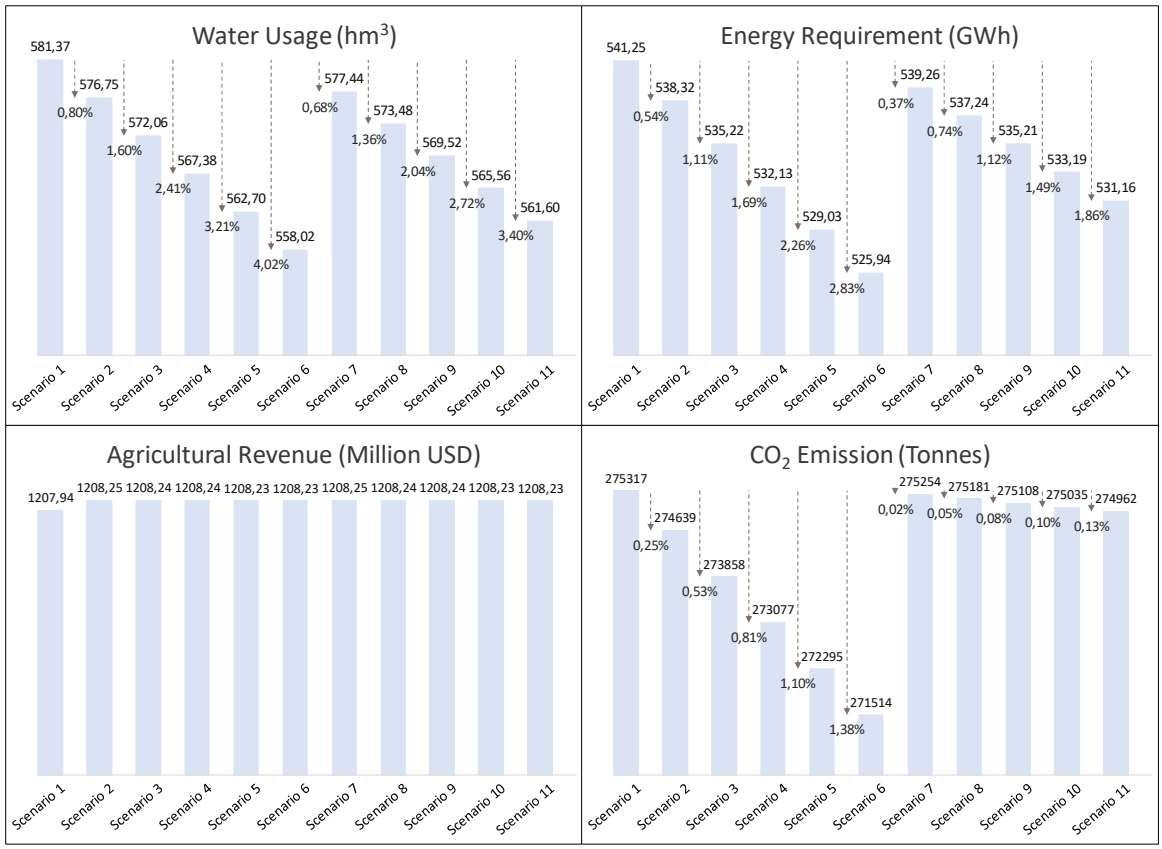


Fig. 3: Results and comparisons of the scenarios for the year 2017

of these results, are illustrated in Fig. 4.

The analysis of the scenarios projected for the period from 2025 to 2050 indicates that scenario 6 achieved the most pronounced reduction in water usage, with a total decrease of 28.8 million m³, representing a proportional decline of 3.96% against the base scenario. In contrast, scenario 11 recorded a decrease of 24.8 million m³, which corresponds to a proportional decline of 3.41% in comparison to the baseline scenario. The most substantial reductions in energy requirements were found in scenario 6, with a decrease of 2.95%, followed by scenario 5 with a decrease of 2.36%. Agricultural revenue exhibited a consistent pattern across all scenarios analyzed.

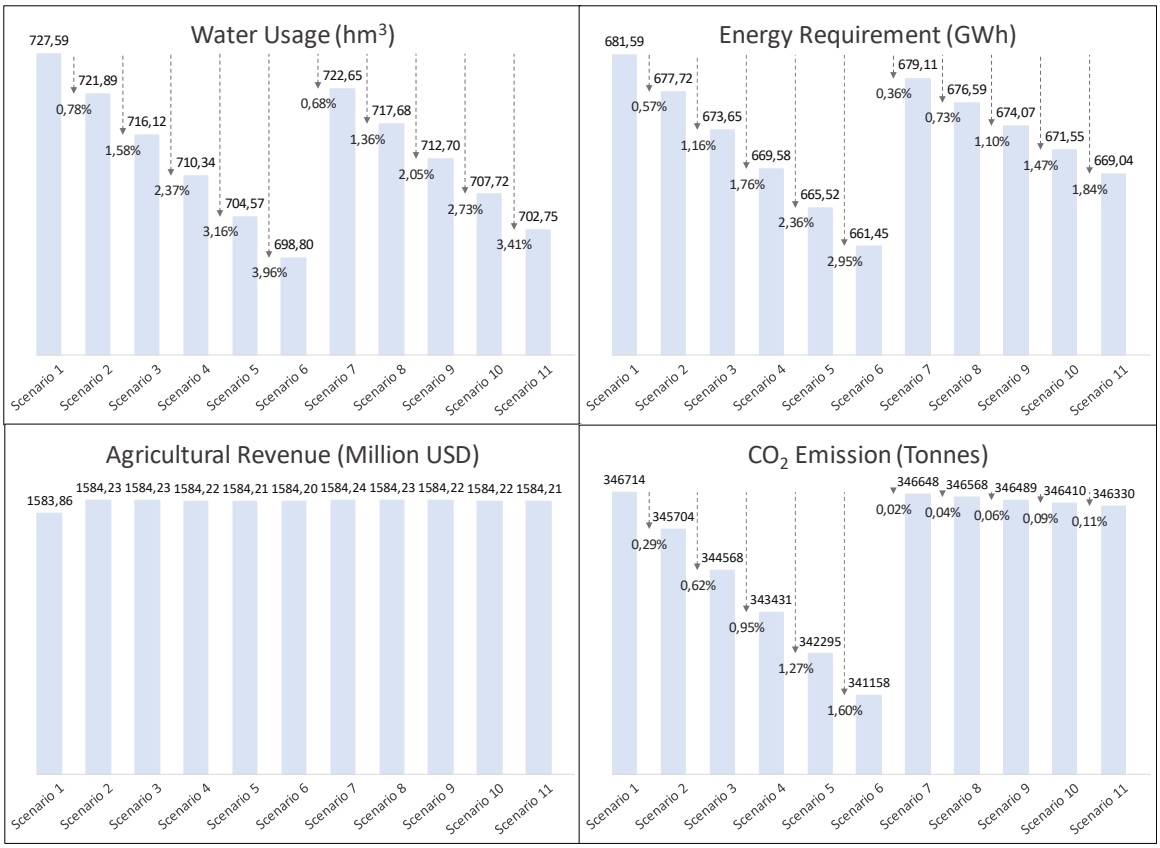


Fig. 4: Results and comparisons of the scenarios for the period 2025-50

Carbon dioxide emissions experienced a decline in every scenario, with the most pronounced reductions observed in scenario 6 at 1.6% and scenario 5 at 1.27%. Results obtained from the scenarios examined for the period 2050-2075 and comparisons of the scenario results are presented in Fig. 5.

Upon reviewing the outcomes for the 2050-2075 timeframe, it is evident that scenario 6 leads to the most significant reduction in water usage, totaling 37.2 million m³. This reduction reflects a proportional decrease of 3.89% when compared to the baseline. Scenario 11 exhibits substantial reductions, with a decrease of 33.3 million m³, reflecting a proportional decrease of 3.49% compared to the base scenario. The most notable decreases in energy requirements are found in scenario 6, with a reduction of 3%, and in scenario 5, with a decrease of 2.39%. Agricultural revenue exhibits a stable pattern across all examined scenarios. Notably, CO_2 emissions have experienced a decline in every scenario, with the most pronounced reduction occurring in scenario 6 at 1.7%, followed closely by a 1.35% decrease in scenario 5. Results obtained from the scenarios examined for the period 2075-2100 and comparisons of the scenario results are given in Fig. 6.

Upon reviewing the outcomes of the scenarios for the years 2075 to 2100, it is evident that scenario 6 achieved the highest reduction in water usage, totaling 46.6 million m³. This represents a proportional decline of 3.87% in comparison to the baseline scenario. Scenario 11 showed significant reductions, with a decrease of 42.1 million m³, representing a proportional decline of 3.5% compared to the base scenario. The greatest decreases in energy requirements were observed in scenario 6 with a reduction of 3.03%, and in scenario 5 with a decrease of 2.42%. Agricultural revenue showed a consistent pattern across all scenarios. Carbon

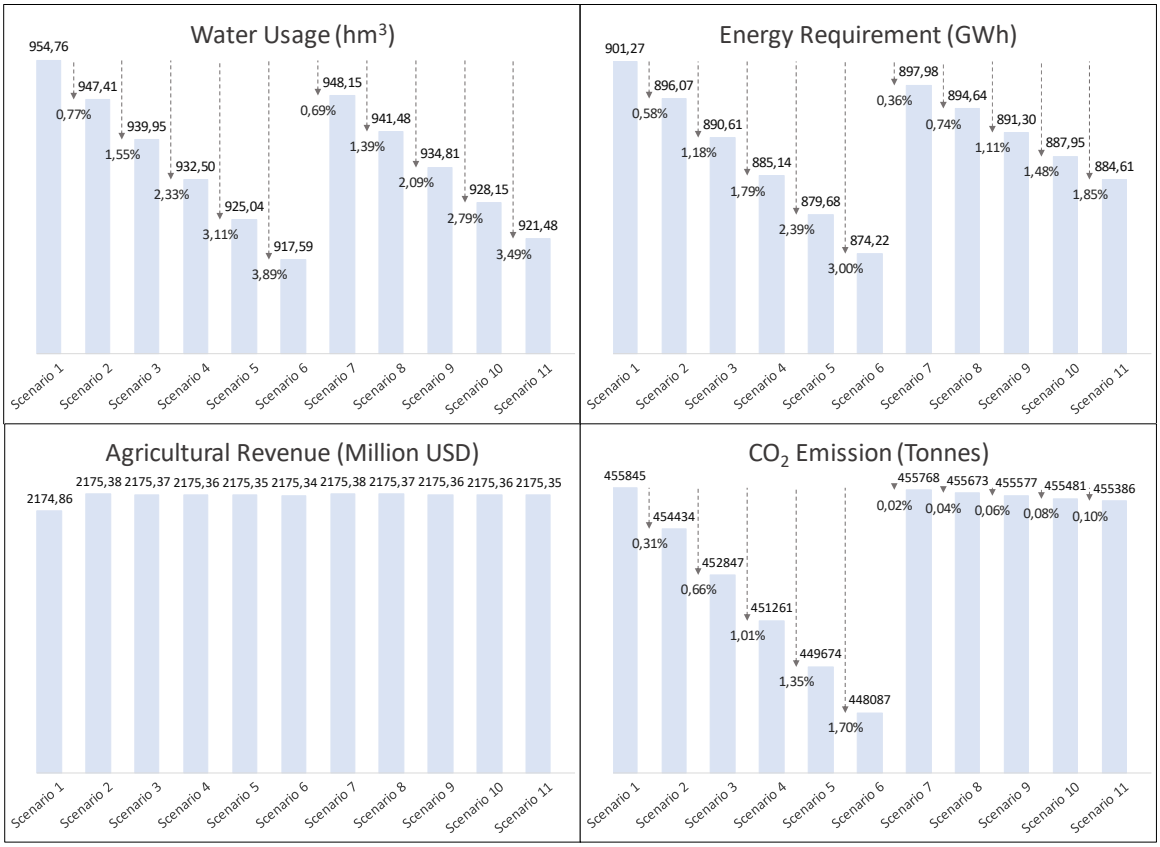


Fig. 5: Results and comparisons of the scenarios for the period 2050-2075

dioxide emissions decreased in every scenario, with the most significant reduction observed in scenario 6 at 1.78%, followed by a 1.42% decrease in scenario 5. In this study, a water-centered perspective is adopted, focusing on potential water savings that can be achieved in agricultural production while considering constraints such as maintaining the current agricultural income level, limiting changes in cultivation areas for each crop, and preserving the total cultivation area. The findings indicate that significant reductions in water consumption, energy demands, and CO_2 emissions can be realized by altering cropping patterns, with agricultural revenue remaining relatively stable. Different objectives and approaches may be prioritized in optimization models. Most of the previous studies have primarily concentrated on boosting income. A thorough analysis of the studies performed demonstrates that, even with differing aims, the constraints implemented exhibit significant similarities. Osama *et al.* (2017) focused on maximizing the total net benefit as the primary objective in determining the optimal cropping pattern, taking into account constraints such as water availability, total land area, and planting area over a five-year period from 2008 to 2012. After optimization, the gross net benefit increased by an average of 6.44% over the five-year period compared to the previous cropping pattern. Daghighi *et al.* (2017) selected increasing the profit to be made from the agriculture as target function using 2015 as the reference year and determined the optimal cropping patterns for every five-year interval from 2020 to 2040. The constraints imposed encompassed a maximum allowable variation of 20% in the areas designated for cropping, restrictions on the volume of irrigation water available, and the distribution of water resources contingent upon the specific types of crops being cultivated. The final net profit increased by 8% compared to the reference year. In their study, Kumar *et al.* (2022) employed

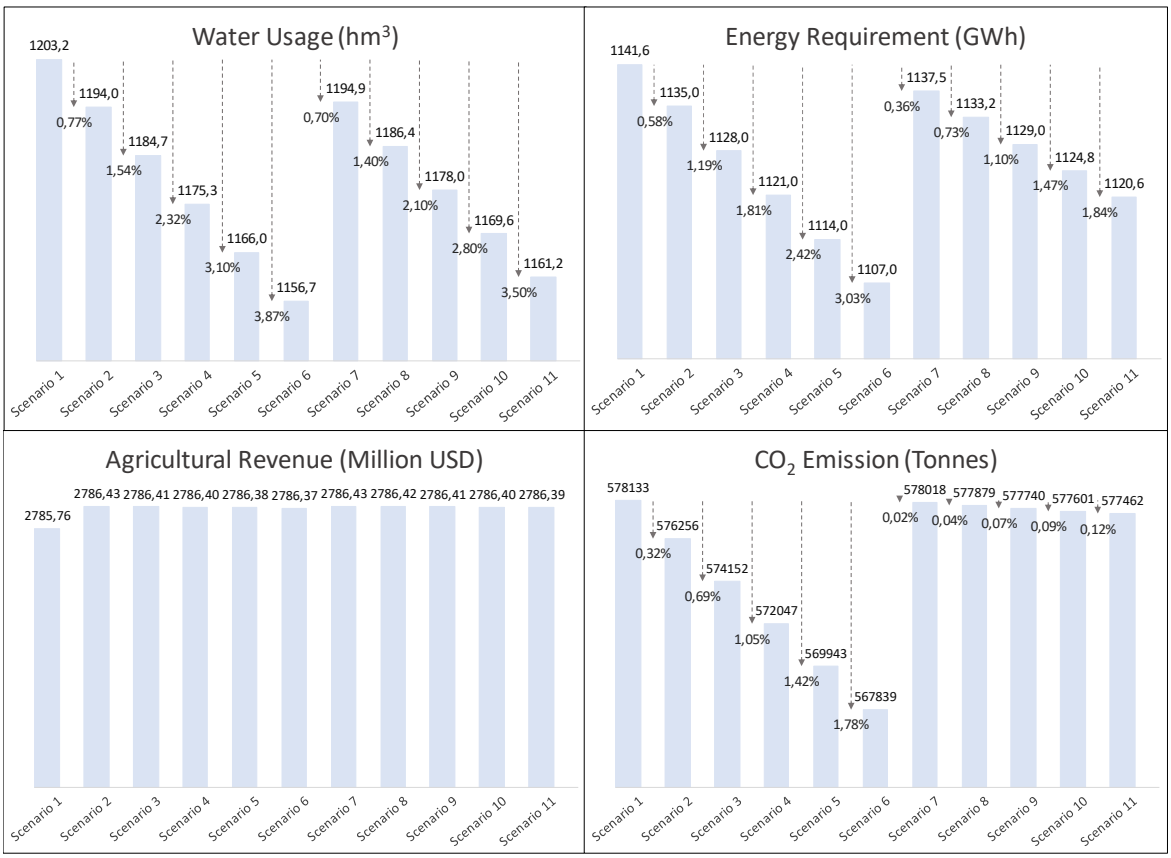


Fig. 6: Results and comparisons of the scenarios for the period 2075-2100

LP to maximize net returns and identify the optimal crop pattern while considering constraints related to water availability, total land area, farmers' crop preferences, crop acreage, and available fertilizers. Saray *et al.* (2022) developed and calculated a water-energy-food nexus index by analyzing water and energy consumption and productivity metrics, using data collected from a farm within their study area. Two distinct scenarios were examined to identify the most effective cropping patterns: the first aimed at enhancing the water-energy-food nexus index, while the second sought to reduce CO_2 emissions. Each scenario was constrained by limitations on the total area available for cultivation and the distribution of land across various crops. The approach focused on minimizing CO_2 emissions yielded better results in reducing water and energy consumption as well as CO_2 emissions. This approach also led to a decrease in food production. Tajbakhsh *et al.* (2018) proposed a comprehensive model for optimizing land allocation aimed at minimizing surface runoff and sediment load while maximizing net income. This model utilized weighted goal programming, the analytic hierarchy process, and multi-objective land allocation algorithms. Their approach resulted in a 16.78% reduction in sediment load and a 72.52% increase in net income, though it also led to a 0.22% increase in runoff volume. Hrytsiuk *et al.* (2019) applied Markowitz's optimal portfolio theory to redistribute existing grain crop areas with the goal of enhancing production efficiency. The findings of their analysis indicated that the profitability of crops adheres to a Laplace distribution instead of a normal distribution. Consequently, through optimization, they developed efficient frontiers for portfolios of cereal crop sown areas in the Rivne region by conducting numerical risk evaluations. The main limitations and uncertainties encountered in studies

aimed at determining the optimal cropping pattern can be listed as the need to make changes within certain limits in cultivation areas to ensure sufficient food supply, availability of land for agricultural activities, variability in economic paremeters, climatic characteristics for future periods. The emphasis on single-objective optimization within the context of various constraints to identify optimal cropping patterns represents a methodological limitation. In the realm of agricultural crop planning optimization, it is important to recognize the presence of multiple, often conflicting objectives. When dealing with these conflicting objectives, multi-objective methods that reflect various perspectives by assigning different priorities to the goals can also be preferred.

CONCLUSION

This study explored various scenarios to identify the most efficient cropping pattern aimed at reducing water consumption in agricultural production. LP was employed to identify the optimal cultivation zones for each crop type within the basin, aiming to minimize water consumption. In crop pattern change scenarios, constraints for LP were set to be equal to or higher than the agricultural income amount in the base scenario, having the total cultivation area equal to or larger than that in the base scenario, and allowing spatial changes in the cultivation areas within the ranges of 1%, 2%, 3%, 4%, and 5%. Following the analysis of crop patterns derived from linear programming for the years 2017, 2025-2050, 2050-2075, and 2075-2100, the study assessed water consumption, energy demands, agricultural income, and CO_2 emissions for each scenario. This evaluation was conducted within the framework of the FEW nexus, allowing for a comparative analysis of all scenarios. The key novelty of this study lies in incorporating FEW nexus based assessments into the determination of optimal planting patterns. The results and comparisons of the scenarios indicate that substantial decreases in water usage, energy needs, and CO_2 emissions can be accomplished solely through alterations in the crop pattern while the agricultural income largely stays at the same level. The introduction of a constraint within the LP model, which requires the total cultivation area to be at least as large as that of the baseline scenario, has been found to limit the possible reductions. In contrast, scenarios that do not impose a total cultivation area constraint demonstrated more favorable outcomes than those exhibiting comparable percentage changes but constrained by the total cultivation area requirement. Examining various scenarios with different rates of change in planting areas and observing corresponding reductions in agricultural water use, energy requirements and CO_2 emissions highlights the trade-offs involved. When the allowable percentage changes decreased, these output parameters showed smaller reductions, resulting in less favorable outcomes. An increase in the permissible percentage variations in crop acreage led to improved outcomes. An analysis of all time periods revealed that scenario 6 emerged as the most favorable, yielding an average reduction of 3.93% in water consumption, a 2.95% decrease in energy demands, and a 1.62% decline in CO_2 emissions relative to the baseline scenario. Scenario 11 achieved an average water usage reduction of 3.45% across all time periods, ranking it as the second-best scenario for water conservation, but it only managed an average reduction of 1.85% in energy requirements and a mere 0.11% reduction in CO_2 emissions. With a third-place ranking in water use reduction, Scenario 5 achieved an average decrease of 3.15% in water usage, a 2.36% reduction in energy needs, and a 1.29% decline in CO_2 emissions over all analyzed periods. Improvement in all of these outcomes with the proposed model is considered important in terms of contributing to the sustainable management of agriculture. The conclusions drawn from the study are perceived as delivering critical insights to those in decision-making roles, facilitating the advancement of sustainable agricultural production planning in the agriculturally rich areas of the Gediz Basin. Although the results of this study were obtained for a specific region, the applied methodology can be readily adapted for use in various other applications. The fundamental characteristics of linear programming (LP) dictate that the approach is centered around a singular objective function accompanied by linear constraint equations. For a more comprehensive analysis that considers multiple perspectives or approaches simultaneously, future research could benefit from multi-objective optimization to determine optimal cropping patterns.

AUTHOR CONTRIBUTIONS

V. Hacısüleyman performed the literature review, methodology development, interpretation and

visualization of the results and wrote the manuscript. M. Özger supervised the work, conceptualization and manuscript edition.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percentage
CO_2	Carbon dioxide
FAO	Food and agriculture organization
FEW	Food-energy-water
GWh	Gigawatt hours
ha	Hectare
hm^3	Cubic hectometer
kg/ha	Kilograms per hectare
km	Kilometer
km^2	Square kilometer
kWh/m^3	Kilowatt hours per cubic meter
L/ha	Liters per hectare
LP	Linear programming
mm	Millimeter
m^3	Cubic meter
m^3/ha	Cubic meters per hectare
SYGM	General Directorate of Water Management
TurkStat	Turkish Statistical Institute
USD	United States dollar
WEF	Water-energy-food

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