Impacts of irrigation and nitrate fertilization scenarios on groundwater resources quantity and quality of the Almyros Basin, Greece

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ABSTRACT

Irrigation and nitrate fertilization scenarios were combined and simulated for crop water irrigation demands and nitrogen applications based on experiments on crop cultivation practices. Two irrigation practices (deficit irrigation and rainfed conditions) were applied to the main crop types of the Almyros Basin, a coastal basin located in Thessaly, Greece. The Almyros groundwater system suffers from progressive water balance deficit, nitrate contamination and seawater intrusion due to groundwater abstractions for agricultural irrigation to cover crop water demands in the dry season. The impacts of the irrigation and nitrate fertilization scenarios on groundwater resources quantity and quality were simulated using an Integrated Modelling System consisting of models of surface hydrology (UTHBAL), groundwater hydrology (MODFLOW), crop growth/nitrate leaching (REPIC), contaminant transport (MT3DMS), and seawater intrusion (SEAWAT), for the historical period of 1991–2018. The results of the scenarios were evaluated with the indicators of Crop Water Productivity (CWP) for crop yields and irrigation water, Partial Factor Productivity (PFP) for Nitrogen Use Efficiency, and Economic Water Productivity (EWP) for the gross profits of the irrigation water.

Key words | fertilization, groundwater, integrated water resources modelling, irrigation, scenarios, water balance, water quality

HIGHLIGHTS

- The study evaluates the impacts of irrigation and nitrate fertilization scenarios on groundwater resources.
- The Integrated Modelling System of surface hydrology (UTHBAL), groundwater hydrology (MODFLOW), crop growth/nitrate leaching (REPIC), contaminant transport (MT3DMS), and seawater intrusion (SEAWAT) has been enriched to simulate agronomic practices.
- CWP, EWP and NUE indices evaluate the performance of the scenarios.
INTRODUCTION

The impacts of irrigation and fertilization practices on groundwater resources in semi-arid regions is one of the most important water supply problems of irrigated agriculture and water quality deterioration of aquifer systems (Fernández García et al. 2020; Lyra et al. 2021). In coastal water systems, over-pumping for irrigation water supply, the absence of significant surface water reservoir infrastructure (and for this reason the use of surface water), and excessive nitrogen applications for crop growth improvement, have a number of implications for groundwater, notably the water table descent, nitrate contamination and seawater intrusion (Lyra et al. 2021).

The continuing exacerbation of water deficit and groundwater quality poses a threat on the sustainability of irrigated agriculture in coastal regions. The water quality limit for drinking water regarding nitrates is 50 mg/L (NCESD 2018) while for chlorides it is 250 mg/L. According to the European Directives, chloride concentrations in groundwater systems can be between 24 mg/L and 12,300 mg/L depending on aquifer characteristics (EU 2010).

An integrated approach to the sustainability of crop yields and to the control of nitrate fertilization, groundwater abstractions and seawater intrusion is essential for protecting the viability of natural resources. The key points of such an approach are the understanding and assessment of water budget fluxes and safe water quality supply for irrigation and drinking water consumption (Loukas 2010).

In regions where the largest amount of water resources is consumed for agricultural production and the water balance is negative, the estimation of productivity efficiency is of paramount importance. The trend of marketable crop production is directly linked with irrigation water application, while the latter affects the availability of nitrogen in soils and nitrogen leaching to groundwater (Ullah et al. 2019). The indicators of Crop Water Productivity (CWP), Economic Water Productivity (EWP) and Nitrogen Use Efficiency (NUE) are often utilized for various crop irrigation and fertilization practices to define the advantages and the disadvantages of practices (Fixen et al. 2015; Fernández García et al. 2020). CWP is defined as the marketable crop yield in relation to crop evapotranspiration or irrigation water applied, and measures how much 1 m³ of water actually contributes to crop growth in 1 ha (Ullah et al. 2019; Fernández et al. 2020). EWP is the water quantity transformed into marketable crop yield in 1 ha (Fernández et al. 2020). The combined evaluation of EWP and CWP provides a detailed background for the assessment of impacts of irrigation practices (Fernández et al. 2020). Moreover, NUE may be expressed in various terms, either for short-term or long-term estimations, and is affected by irrigation water. For this reason, NUE depends on CWP and affects the marketable EWP (Ullah et al. 2019; Fernández et al. 2020). Thus, the evaluation of the impacts of irrigation and fertilization practices must be targeted at improving the agronomic, environmental and economic status and profits resulting from agricultural water supply (Ullah et al. 2019; Fernández et al. 2020; Lyra et al. 2021).

The scope of this study is to evaluate the impacts of irrigation and fertilization scenarios on groundwater resources, as well as their benefits compared to the current agricultural and water management practices in the Almyros Basin, a coastal agricultural basin in Thessaly, Greece. The evaluation has been performed with the application of an Integrated Water Resources Modelling System developed by the authors (Lyra et al. 2021) and applied to the study area for the simulation of the quantity and quality status of groundwater and
crop yields for various scenarios of irrigation and nitrogen fertilization. The results of each alternative scenario were quantified using the indicators of CWP, NUE and EWP for the simulation period of 1991 to 2018.

METHODS

Study area and database

The main land use of the Almyros Basin is for agricultural fields, with a small percentage of the basin being used for urban, sub-urban and non-cultivated areas. The hydrography of the basin is characterized by ephemeral streams and absence of significant surface water storage works. The cultivated agricultural area covers most of the area of the Almyros aquifer. Areas at higher elevations are covered by natural vegetation (e.g. forests and bushland). The areas cultivated per crop were provided by the Greek Payment Authority of the Common Agricultural Policy (CAP) and grouped into nine main crop types. Cereals, olives groves, vineyards and wheat cultivars are the crops primarily cultivated in the study area for the period of 1991 to 2018. The main land uses and crops of the Almyros Basin for the year of 2010 are shown in Figure 1. The cultivated agricultural lands are totally irrigated, due to the absence of surface water storage works, with water obtained from groundwater. Groundwater also supplies water for urban use and it is taken into account in this study. However, the urban water supply volume is not as high as the water volume abstracted for irrigation. The annual agricultural water supply accounts for 29.7 hm$^3$, on average, while the mean annual urban water supply volume reaches 1.8 hm$^3$ (Lyra et al. 2021).

Agricultural water supply scenarios

The agricultural water demand is defined by the crop water demands for crops cultivated in the Almyros Basin. More than two thirds of the area is permanent cropland, irrigated by groundwater abstractions with private-owned wells. The number of irrigation water wells has been estimated at 2,044, indicating intensive agricultural activities (Lyra et al. 2021). The crop water requirements were estimated in

![Figure 1](http://iwaponline.com/ws/article-pdf/21/6/2748/932610/ws021062748.pdf)
a previous study (Lyra et al. 2021) for each main crop category, based on relevant data provided by Greek Payment Authority of the CAP. The total water losses of irrigation distribution systems in the study area were estimated to 41% of the crop water requirements (Sidiropoulos et al. 2016).

Agronomic scenarios were combined and simulated for irrigation crop water demands and fertilizer applications based on experiments in crop cultivation practices. The main crops irrigated in the study area are alfalfa, cereals, cotton, maize, olive groves, trees, vegetables, vineyards, and wheat. Two irrigation practices were considered: (i) deficit irrigation for all crop types; and (ii) rainfed cultivation for cereals, olive groves and wheat, and deficit irrigation for alfalfa, cotton, maize, trees, vegetables, and vineyards. Additionally, a reduced nitrogen fertilization practice was implemented, based on recent field experiments in Greece and the Mediterranean basin. The irrigation and fertilization practices were coupled and produced four scenarios, as presented in the next paragraphs. The simulation results of the four scenarios were compared with the baseline scenario representing the current irrigation and nitrogen fertilization practices.

In order to define the irrigation and nitrogen fertilization scenarios, a detailed literature review of field experiments performed in Greece and in the Mediterranean area for the main crops of the study area was made. The scenarios developed are based on the reduction of irrigation water applied and nitrate fertilization. The results of field experimental studies used in this paper are outlined below.

According to field experimental research, alfalfa is characterized by high irrigation water needs and low nutrient requirements. Alfalfa presents high productivity (yield) and marketable prices as compared to other crop types and water productivity increase when applying irrigation water equal to 90% of crop water requirements, and nitrogen equal to 28 kg/ha (Djaman et al. 2020). The cereal cultivated in the study area is mainly barley. Barley has medium/low water demands for crop yield in irrigated conditions. The water productivity and crop yield of barley increases when applying water equal to 70 and 80% of crop water requirements (Pardo et al. 2020). The nitrogen fertilization promotes the crop yield of barley and increases the water productivity, with nitrogen application of 60 kg/ha and deficit irrigation practices of 75% of the crop’s water requirement (Barati et al. 2015). Cotton is characterized by medium/high irrigation requirements, but the reduction of irrigation water to 80% of crop water requirements increases crop yield (Polychronides et al. 1998). The nitrogen fertilization of cotton at 109.5 kg/ha increases crop yield and maximizes the economic benefits (Polychronaki et al. 2012). Maize is an irrigated cultivar and the deficit irrigation at 90% of crop water demand indicated that there is no reduction in the crop yield (Fernández García et al. 2020). The nitrogen requirements of maize define its crop yield and the experimental low rate application of 100 kg/ha optimised dry matter yield in deficit irrigation according to Archontoulis and associates (Archontoulis et al. 2010). Orchards were explicitly studied for various agricultural practices, for irrigation and fertilization applications, and their impacts on water quality in the LIFE AgroClimaWater Project. Olive groves can be cultivated rainfed, but this leads to reduction of crop yield. The total irrigation amount applied in olives groves, when reduced at 89% of total crop water requirements combined with a nitrogen application rate of 91.2 kg/ha does not decrease crop yield (Arampatzis et al. 2018). Fruit and other orchards studied in the AgroClimaWater Project averaged values of deficit irrigation practices at 76% of crop water requirements and 73% of nitrogen fertilization for different types of orchards used in the scenarios of the study (AgroClimaWater 2016). For vegetable crop types, different crops were studied according to the literature. The irrigation water productivity of garlic and onions increases when the irrigation water is reduced at 70 and 90% of irrigation requirements, respectively (Fernández García et al. 2020). Tomatoes irrigated at a deficit of 75% of crop irrigation demands and fertilized at 120 kg/ha reach optimal crop yield scores (Kuscu et al. 2014). For these reasons an averaged amount of 80% reduction in nitrogen fertilization was considered for the vegetable crop type. Vineyards are susceptible to agronomic alterations and therefore the deficit irrigation at 60% of crop water demands combined with nitrogen application of 60 kg/ha, lower than the typical fertilization practices in the region, was considered in the study (Thomidis et al. 2016). Similarly to barley and cereals, the crop yield of wheat is increased, and also crop water productivity, at deficit irrigation between 60 and 85% (Ullah et al. 2019). Nitrogen fertilization application has been reported to
reach optimum wheat yield at 102 kg/ha (Polychronaki et al. 2012).

The developed scenarios included combinations of irrigation and nitrogen fertilization practices. Four scenarios were developed: scenario S1 combines baseline current fertilization and deficit irrigation conditions for all crops, while scenario S2 combines baseline current fertilization and rainfed cultivation for cereals, olive grove and wheat, and deficit irrigation for alfalfa, cotton, maize, trees, vegetables, and vineyards. Scenario S3 combines reduced fertilization and deficit irrigation for all crops, while scenario S4 combines reduced fertilization and rainfed cultivation for cereals, olive grove and wheat, and deficit irrigation for alfalfa, cotton, maize, trees, vegetables, and vineyards. The consideration of a scenario with no fertilization is not applicable because the crop yields of the crop types are greatly affected by nitrogen availability (Ullah et al. 2013). The four developed scenarios were compared with a baseline scenario (S0) representing the current irrigation and nitrogen fertilization practices. The irrigation water and nitrogen fertilization applications are presented in Table 1.

**Drinking water supply**

The population of the Municipal Districts and Local Communities of Almyros were considered using the censuses of 1991, 2001 and 2011 (permanent population) by the Hellenic Statistical Authority. Drinking water supplies from groundwater covered the water needs of 21,583 people in 1991, 22,191 in 2001 and 19,405 in 2011. The urban water supply in the area of Almyros is supplied by a total of 28 wells. The possible increase in summer urban water demands is also covered by groundwater abstractions of neighbouring water systems that do not interact with the aquifer system of Almyros, and by water tanks that reserve surplus groundwater abstractions in times of low consumption. The average daily consumption per inhabitant was set at 170 L/inhabitant/day and the water losses of the distribution network were estimated to 40%. The monthly distribution of groundwater abstractions for the drinking water demands was estimated, during the calibration and validation procedures of the Integrated Modelling System, at 13% in October, 10% in November, 8% in December, 6% in January, 5% in February, 5% in March, 6% in April, 6% in May, 8% in June, 10% in July, 12% in August and 12% in September. These figures agree well with the results of a study in the nearby city of Volos (Mylopoulos et al. 2001). The total drinking water demands were estimated to 1.87 hm³ for the period 1991–2000, 1.93 hm³ for the period 2001–2010, and 1.69 hm³ for the period 2011–2018.

**Integrated modelling system**

The water quantity and quality of the Almyros Basin for the alternative scenarios was simulated using an Integrated Water Resources Modelling System developed by the authors (Lyra et al. 2021). The modelling system consists of coupled and interrelated models of surface hydrology (UTHBAL) (Loukas et al. 2007), groundwater hydrology (MODFLOW) (Harbaugh et al. 2000), crop production/nitrate leaching (REPIC) (Lyra et al. 2021), nitrate transport (MT3DMS) (Zheng & Wang 1999), and seawater intrusion.

### Table 1 | Maximum annual irrigation water and nitrogen fertilization applications

| Crop Type | Baseline Irrigation [mm] | Deficit Irrigation [mm] | Deficit Irrigation/ Rainfed [mm] | Baseline N fer [Kg/ha] | Reduced N fer [Kg/ha] |
|-----------|--------------------------|-------------------------|---------------------------------|------------------------|-----------------------|
| Alfalfa   | 893                      | 804                     | 804                             | 30                     | 28                    |
| Cereals   | 336                      | 269                     | 0                               | 100                    | 60                    |
| Cotton    | 409                      | 327                     | 327                             | 140                    | 110                   |
| Maize     | 389                      | 350                     | 350                             | 325                    | 100                   |
| Olives    | 515                      | 407                     | 0                               | 125                    | 100                   |
| Trees     | 515                      | 390                     | 390                             | 175                    | 128                   |
| Vegetables| 271                      | 244                     | 244                             | 150                    | 120                   |
| Vineyards | 297                      | 178                     | 178                             | 125                    | 60                    |
| Wheat     | 336                      | 269                     | 0                               | 160                    | 102                   |
SEAWAT (Guo & Langevin 2002) (Figure 2). The modelling system was successfully calibrated and validated in Almyros Basin simulating with improved accuracy the groundwater flow, the nitrate contamination, the seawater intrusion and the crop yields (Lyra et al. 2021). In this study, the modelling system was used for the simulation of the irrigation and nitrogen fertilization scenarios for the period 1991–2018. The goodness-of-fit statistics for the calibration and validation of the models of the Integrated Water Resources Modelling System can be found in the Supplementary Material of the paper.

Indicators

The CWP and EWP indices regarding the irrigation water applied and the grain yield were implemented for the evaluation of the simulation results for the Almyros Basin. The CWP for irrigation water is calculated by Equation (1) (Fernández et al. 2020):

\[
\text{Crop Water Productivity (CWP)} = \frac{\text{Crop Yield } \text{kg ha}^{-1}}{\text{Irrigation Water } \text{m}^3\text{ha}^{-1}}
\]  

(1)

For the calculation of the EWP indicator for irrigation water, public annual data for the crop price index from 2000–2018 with base year 2015, were obtained by the Hellenic Statistical Authority for the main crops cultivated in the Almyros Basin. The EWP is calculated by Equation (2) (Fernández et al. 2020):

\[
\text{Economic Water Productivity (EWP)} = \frac{\text{Profit } \text{ha}^{-1}}{\text{Irrigation Water } \text{m}^3\text{ha}^{-1}}
\]  

(2)

The NUE is estimated in terms of Partial Factor Productivity (PFP) appropriate for long-term estimations of crop yields and nitrogen applications, by Equation (3) (Fixen et al. 2015):

\[
\text{Partial Factor Productivity (PFP)} = \frac{\text{Crop Yield } \text{kg ha}^{-1}}{\text{Nitrogen Applied } \text{kg ha}^{-1}}
\]  

(3)

RESULTS AND DISCUSSION

UTHBAL model

The results obtained from the application of the UTHBAL model in the Almyros Basin in the earlier study (Lyra et al. 2021) for the period 1991–2018 were used in the simulation of the four developed scenarios. The goodness-of-fit statistics for the calibration and validation of the models of the Integrated Water Resources Modelling System can be found in the Supplementary Material of the paper.

MODFLOW model

The groundwater fluxes were simulated for the period of 1991 to 2018 for the scenarios of deficit irrigation (S1, S3) and deficit and rainfed conditions (S2, S4). The simulated groundwater heads for the four scenarios (i.e. S1, S2, S3, S4) were compared with the respective simulated results for the baseline scenario (S0) for the end of the simulation period (2018) in Figure 3. The baseline scenario (S0-continuous line) and the scenarios of deficit irrigation (S1, S3- dashed line) present a closely related variation of the water table especially in the lowland areas. The deficit irrigation and rainfed cultivation results (scenario S2, S4- dashed dot line) show slightly different hydraulic heads in the central southern parts of the aquifer where the hydraulic conductivity is low. The hydraulic heads for both irrigation scenarios (i.e. S1-S3 and S2-S4) at the end
of the simulation period are higher than the baseline scenario (S0) (Lyra et al. 2021), indicating an increase in the elevation of the groundwater water table.

**REPIC model**

The crop yields of the main crops of the Almyros Basin were simulated by the REPIC model, for irrigation and fertilization scenarios for the period 1991–2018. The results of crop yields for the simulated land use periods for the baseline scenario, S0, and the alternative scenarios S1, S2, S3 and S4 are presented in Figure 4. Although, deficit irrigation and rainfed cultivation were considered, there is no significant change of the yields of the other crops for the alternative scenarios. The results indicate that the yield of vineyards, olive groves and cotton are affected by the reduction of irrigation water and nitrogen fertilization.

**MT3DMS model**

The nitrate fluxes were simulated by the MT3DMS model for the period of 1991 to 2018. The simulation was performed for all four scenarios (S1, S2, S3, S4). The differences between the simulation results for the baseline scenario, S0, and scenarios S3 and S4 are shown in Figure 5(a) and 5(b), respectively. The simulation results show that the nitrate contamination in the aquifer is mostly affected by the irrigation practices and irrigation return flow, due to the semi-arid climate and the low recharge, especially, in the southern parts of the aquifer. The nitrate concentrations of scenario S4 are spatially lower than the results for scenario S3. Although in scenario S4, a large part of the aquifer is rainfed and nitrate fertilization is reduced, the results show no reduction of the nitrate concentrations in the central coastal part, mainly due to the low recharge from precipitation and thus reduced dissolution of the contaminant. Particularly, in the low recharged and low hydraulic conductivity areas, the presence of irrigated and fertilized maize cultivars, adjacent to rainfed crops, causes the local persistence and assimilation of nitrates.

**SEAWAT model**

The chloride fluxes were simulated using the SEAWAT model for the period of 1991 to 2018 and the simulation was performed for all four scenarios (S1, S1, S3, S4). The differences of the simulation results of scenario S3 and scenario S4 from the baseline scenario S0 are depicted in Figure 5(c) and 5(d), respectively. The reduced irrigation scenarios have a positive influence on the delay of the evolution of seawater intrusion, as compared to the irrigation practices of the baseline scenario S0. The maximum chloride concentration reduction in all scenarios reaches a value of 18,000 mg/L in the north coastline area that is salinized in the baseline scenario S0 (Lyra et al. 2021). Although, scenarios S1 and S3 show a spatial average reduction of 36 mg/L, and scenarios S2 and S4 a spatial average of 26 mg/L, the latter have a larger extent of positive impact on the aquifer’s water quality (Figure 5(d)).
Water budget

The average monthly (Figure 6(a)) and annual (Figure 6(b)) water budget of the Almyros Basin aquifer for the deficit irrigation scenarios (S1, S3), and the deficit irrigation and rainfed cultivation scenarios (S2, S4), were calculated and compared to the current historical groundwater regime of the Almyros aquifer for the simulation years 1991–2018. Due to the large extent of the spatial distribution of cereals and wheat, the deficit irrigation scenarios (S1, S3) show a monthly higher positive inflow, which is attributed to the irrigation return flows, as compared to the scenarios of deficit irrigation and rainfed cultivation (S2, S4), when groundwater is only recharged by the infiltration of precipitation. The annual water deficit of the baseline scenario S0 is 12.02 hm$^3$ (Lyra et al. 2021), minimized in the deficit irrigation case to 2.3 hm$^3$ (scenarios S1 and S3), and in the deficit irrigation and rainfed cultivation case (scenarios S2 and S3) to 2.8 hm$^3$. The annual water deficit for the deficit irrigation and rainfed cultivation case is larger than the water deficit for the deficit irrigation case alone, due to the limited natural recharge and absence of irrigation return flow for a large extent of the aquifer area. Nevertheless, both practices have a significant positive impact on the water balance.

Crop water productivity

The CWP indicator was estimated using Equation (1) for every main crop of the Almyros Basin, based on the results of the REPIC model for crop yields, and on the irrigation water demands for the baseline scenario S0 and the scenarios S1, S2, S3 and S4. The comparative percentages of
CWPI for the scenarios from the baseline scenario S0 are presented in Figure 7(a). The CWPI is increased for the deficit irrigation conditions (i.e. S1 and S3) for all crops in the Almyros Basin.

Partial factor productivity

The PFP indicator was estimated using Equation (3) for the evaluation of the efficiency of nitrogen use on crops on the simulated scenarios for baseline fertilization (S1, S2) and reduced fertilization (S3, S4). In the reduced fertilization practices in all crop types, except for alfalfa, PFP is increased, especially for cereals, maize, vineyards, and wheat. The comparative percentages of the variations of the indicator from the baseline scenario S0 scores are presented in Figure 7(b).

Economic water productivity

The EWP indicator was estimated using Equation (2) for the irrigation water applied. The calculation was performed based on the averaged grain yield prices with base year 2015. The scores for EWP1 are presented in Table 2. The EWP1 of the crop pattern is increased in scenarios S1 and S3 while their scores indicate that the fertilization practices have minimum total impact on crop yields.

CONCLUSIONS

Irrigation water and nitrogen fertilization applications were simulated for the assessment of their impact on the groundwater quantity and quality of the Almyros Basin. The Integrated Water Resources Modelling System applied has been expanded to include the simulation of agronomic and irrigation practice alterations. All the scenarios (S1, S2, S3, S4) have a positive impact on the water balance, and the water deficit is reduced significantly by 9.7 hm³ in scenarios S1 and S3, and 9.2 hm³ in scenarios S2 and S4. The larger water deficit in scenarios S2 and S4 is caused by the absence of irrigation return flows in the rainfed...
areas. Therefore, the latency of seawater intrusion is succeeded in the northern coastline area under all scenarios, and in scenarios S2 and S4 the aquifer’s chloride concentrations are more reduced than in scenarios S1 and S3. The scenario practices show positive impacts on nitrate contamination, especially in scenarios S2 and S4. The nitrate concentrations are reduced in large extent and in all cases, but the irrigated and fertilized maize adjacent to areas of rainfed crops cause local assimilation of nitrates and have a negative impact on the aquifer’s water quality. The crop yield results show that vineyards are susceptible to deficit irrigation, while cereals, maize and wheat are resilient to changes in agronomic practices. All crops had an improved CWP in all scenarios, as compared to baseline scenario S0, reaching maximum scores in baseline fertilization practices. Consequently, the EWP of the crop pattern reached an optimum score of 1.29 €/m³ in scenario S1. However, the crops’ PFP was increased when reducing nitrate fertilization in scenarios S3 and S4, especially for cereals, maize, vineyards, and wheat. In total, the results indicate that the higher positive impacts on groundwater quantity and quality are achieved in scenarios S2 and S4. The further improvement of groundwater quantity and quality may be achieved by changing the

![Figure 7](https://iwaponline.com/ws/article-pdf/21/6/2748/932610/ws021062748.pdf)

**Table 2** Average of economic water productivity (EWP) of irrigation water applied per crop type and scenario with base year 2015

| €/m³ | Alfalfa | Cereals | Cotton | Maize | Olive groves | Trees | Vegetables | Vineyards | Wheat | Crop Pattern |
|------|---------|---------|--------|-------|-------------|-------|------------|----------|-------|-------------|
| S0   | 0.62    | 0.46    | 0.91   | 1.15  | 1.85        | 0.58  | 17.28      | 2.70     | 0.49  | 1.08        |
| S1   | 0.68    | 0.58    | 1.11   | 1.28  | 2.34        | 0.75  | 19.16      | 3.95     | 0.61  | 1.29        |
| S2   | 0.68    | –       | 1.11   | 1.28  | –           | 0.75  | 19.16      | 3.69     | –     | 0.82*       |
| S3   | 0.68    | 0.58    | 1.08   | 1.28  | 2.34        | 0.75  | 19.16      | 3.95     | 0.61  | 1.28        |
| S4   | 0.68    | –       | 1.09   | 1.28  | –           | 0.75  | 19.16      | 3.69     | –     | 0.82*       |

*Irrigated crops.*
crops’ cultivation patterns. The simulation of various crop pattern scenarios may reveal more about the optimal implementation of agricultural management strategies.

FUNDING

This research is co-financed by Greece and the European Union (European Social Fund–ESF) through the Operational Programme ‘Human Resources Development, Education and Lifelong Learning’ in the context of the project ‘Strengthening Human Resources Research Potential via Doctorate Research’ (MIS-5000432), implemented by the State Scholarships Foundation (IKY).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 31 January 2021; accepted in revised form 23 March 2021. Available online 2 April 2021