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Model Application for Estimation of Agri-Environmental Indicators of Kiwi Production: A Case Study in Northern Greece

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Abstract: Due to the sensitivity of kiwifruit to soil water and nutrient availability, kiwi production is often associated with over-watering and over-fertilization, especially with nitrogen (N), resulting in increased environmental risks. Crop models are powerful tools for simulating crop production and environmental impact of given management practices. In this study, the CropSyst model was applied to estimate soil N budget and environmental effects of kiwi production, with particular regard to N losses, in two grower-managed kiwi orchards in northern Greece, involving two seasons and different management practices. Management options included N fertilization and irrigation. Model estimates were compared with yield and soil mineral N content (0–90 cm depths) measured three times within the growing season. Agri-environmental indicators were calculated based on the N budget simulation results to assess the environmental consequences (focusing on N losses and water use efficiency) of the different management practices in kiwi production. According to model simulation results, kiwifruit yield and N uptake were similar in both orchards. N losses to the environment, however, were estimated on average to be 10.3% higher in the orchard with the higher inputs of irrigation water and N fertilizer. The orchard with the lower inputs showed better water and N use efficiency. N leaching losses were estimated to be higher than 70% of total available soil N in both study sites, indicating potential impact on groundwater quality. These findings demonstrate the necessity for improved irrigation and N fertilization management in kiwi production in the area.

Keywords: CropSyst; kiwifruit; irrigation; nitrogen fertilizer; soil N budget; agri-environmental indicators

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1. Introduction

Kiwi (*Actinidia deliciosa* (A. chev.) C.F. Liang et A.R. Ferguson var. *deliciosa*) is a deciduous vine indigenous to the mountainous regions of central and southwestern China. Approximately 85% of the world production of kiwi is from China, New Zealand, Italy, and Greece [1]. The world production of kiwifruit was estimated at 4.4×10^6 Mg in 2020 [1]. The consumption of kiwifruit is increasing each year in central Europe, indicating an expanding market. In Greece, the annual production of kiwi was 256.1×10^3 Mg in 2019 which corresponds to a production area of 10.4×10^3 ha [2]. Kiwi orchards are often a monoculture and intensively irrigated, especially in the northern part of Greece. In these areas, farmers have been systematically occupied with kiwi production since the second half of the 20th century. In Greece, the dominant kiwifruit cv. since 1973 has been Hayward. However, selection among 15,000 seedlings originating from open-pollinated 'Hayward' plants in northern Greece in 1989 by the farmer Christos Tsechelidis resulted in the cv. Tsechelidis [3]. In the region of Pieria, kiwi production is a dynamic agricultural activity and represents 60% of Greek production with an area covering 3.1×10^3 ha.

Kiwifruit requires high amounts of irrigation water when cultivated in Mediterranean regions, which are characterized by high light intensities, low precipitation, and relatively high vapor pressure deficits [4]. In these growing conditions, kiwifruit seasonal irrigation volumes can reach about 10–12 $\times$ 10^3 m^3 ha^{-1} [5]. Farmers tend to over-water kiwi since it leads to larger fruits, but this reduces their dry mass and jeopardizes their maintenance after harvest [6]. The risks of over-watering range from groundwater depletion to plant suffocation. In addition, water management has an important effect on kiwifruit production. Evapotranspiration in kiwi orchards increases with increasing levels of water applied and is dependent on water demand, applied water, irrigation method used, canopy cover, and water management. In view of the reduced water availability for the agricultural sector and the foreseen climate change, it is important to develop innovative and more efficient irrigation strategies for optimizing the crop's irrigation scheduling [7]. Proper irrigation water management in kiwi production will provide high yields of high-quality fruits, having a considerable effect on the orchard's profitability.

The mineral composition of kiwifruit is an important factor for its quality, in particular its nutritional properties. Adult kiwifruit requires approximately 150 kg N ha^{-1} $year^{-1}$ [8]. N fertilization is the key factor for obtaining significant fruit yield in terms of quantity and quality and ensuring the economic viability of the orchard. More than half of the global population is fed by crops grown with the use of synthetic N fertilizers [9]. However, only about half of the N fertilizer applied to soil is typically consumed by crops, while the other half either remains in soil or is lost from fields into the water and atmosphere [10,11], posing health, environmental, and economic problems [12]. Excessive application of N fertilizer in relation to crop N requirements can negatively impact fruit quality after harvest and during storage and results in large amounts of residual nitrate N in soil [13] which can be easily leached into deep soil layers, causing substantial negative environmental impacts [14].

N losses to the environment from agricultural activities constitute one of the prime polluting factors potentially resulting in severe environmental impact through greenhouse gas emissions (nitrous oxide and ammonia) to the atmosphere and losses of nitrate and organic N compounds to water bodies [12,15]. Agri-environmental indicators are considered a useful tool to assess the sustainability of different agricultural management systems [15,16]. Although combining soil testing, N fertilizer experiences of the farmer, and projected crop N requirement (expected yield) is a good method for determining N fertilizer application rates [17], it is rather difficult to manage the fate of N in cropping systems aiming to maintain yield increases with the world's limited land resources [18,19]. Increased yields require a larger pool of plant-available soil N to increase crop growth, but this is more prone to N losses from volatilization, denitrification, and leaching [18]. According to Müller et al. [20], carbon footprints of kiwifruit orchards could be decreased by more accurately adjusting fertilization to crop requirements by monitoring and accounting for plant-available soil N. The plant-available soil N pool, however, is rather difficult to predict and manage [18,19].

Crop growth simulation models have been widely applied for optimizing water and N management in agriculture [21] and are powerful tools in providing information regarding the ability of given management practices to increase productivity while minimizing the environmental impact [22–24] for increasing the agroecosystem efficiency. The simulation of crop growth is based on a complex interaction between weather parameters, soil properties, plant characteristics, and management practices which influence crop response to various water and nutrient inputs [25]. The use of crop growth models in agriculture favors the management of water and nutrient resources and supports comparing different management scenarios that aim at the reduction of non-beneficial resource uses and the increase in crop productivity and economic farm revenue [26]. An increasing number of models have been adapted for specific purposes and scales of application using different input variables and crop growth engines [27–29].

In spite of the large number of studies on model calibration and validation regarding crop growth and development, there are few papers in the literature about the evaluation of crop models for simulating water and nutrient dynamics. The CropSyst model was evaluated for simulating the N balance in field experiments carried out in northern Italy between 2002 and 2004 [30]. The results showed the robustness of the model in reproducing the course of the measured soil mineral N content and the same level of reliability while simulating the N balances under different levels of N fertilization, thus depicting it as suitable for comparing N fertilization scenarios. In a study conducted by Tahir et al. [31] where the Agricultural Production System Simulator (APSIM) model [32,33] was used to simulate soil N in black soil in China for 20 years, the observed values were consistent with the simulated values of N dynamics, denitrification, and N losses through different soil depths. A field experiment was carried out in New Delhi [34] to quantify the N dynamics in rice crops using the InfoCrop model. Simulated results matched well with the observed values in terms of yield of rice and seasonal N uptake with the components of soil N balance (denitrification, volatilization, N_2O emissions) differing among varying N level treatments.

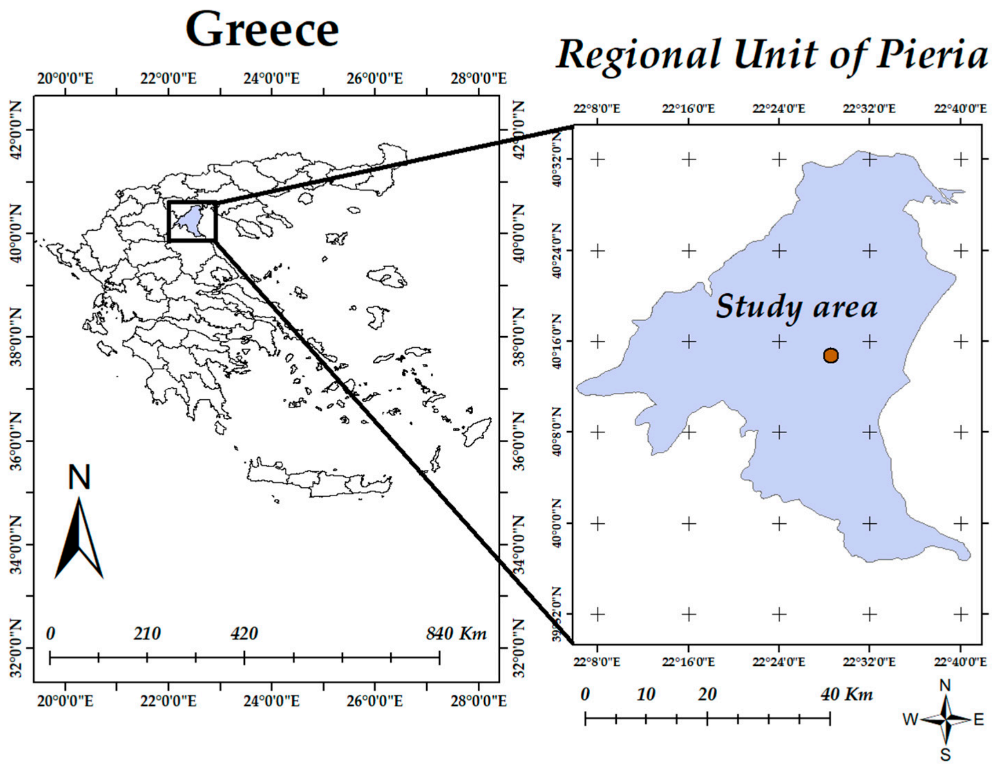
The Cropping Systems (CropSyst) simulation model [35] is a multi-year multi-crop simulation model developed to study the effect of cropping systems management on productivity and environment and has been used to simulate the growth of several crops with generally good results in many parts of the world [36]. The model appears a promising tool for analyzing management practices regarding water and nitrogen [22]. CropSyst was developed with a focus on crop processes and has fundamental differences from approaches adopted by other models such as the Erosion–Productivity Impact Calculator (EPIC) [37] which was originally developed for erosion prediction but has also been applied for cropping systems analysis. Moreover, the water budget in CropSyst shows distinctive features not found in other management-oriented crop growth models. The simple approach of nitrogen transport in CropSyst is preferable compared to models such as the LEACHM model [38] which is more complex with greater input data requirements and longer execution time. Hence, the use of the CropSyst model can lead to a better understanding of the crop response under different environmental conditions and management practices in agriculture.

This paper investigates the effects on soil N dynamics of irrigation and N fertilizer practices, in two grower-managed kiwi orchards in the area of Pieria in northern Greece. The research aim was to set up a crop model to compare the effects on the environment, with particular regard to N losses and water use efficiency of local current management practices in kiwi production. The CropSyst model was used to simulate crop yield and N budget. Model estimates were compared with field data of yield and soil mineral N content (0–90 cm depths) measured three times within the growing season, for two consecutive years. The specific objectives of the study were (1) to estimate the effects of irrigation and N fertilization management practices on N budget using the CropSyst model and (2) to evaluate the potential environmental impact of the different management practices using agri-environmental indicators. To the best of our knowledge, there is limited published research on environmental assessment of kiwi production in the wider area of northern Greece, where the majority of Greek kiwi production takes place. This paper adds knowledge to the research on environmental consequences of the production of kiwi, a non-traditional crop in the Mediterranean region.

2. Materials and Methods

2.1. Study Site Description

The study area was located in the regional unit of Pieria, region of Central Macedonia, northern Greece (Figure 1a). Kiwi (*Actinidia deliciosa*) production was monitored in two nearby, smallhold, grower-managed orchards: plots A and B (Figure 1b), for two consecutive growing seasons (2020 and 2021). Plot A (40°14′22.43′′ N, 22°29′1.53′′ E), with elevation of 32 m above sea level (a.s.l.), covered an area of 0.50 ha. Plot B (40°14′44.73′′ N, 22°28′35.39′′ E), with elevation of 32 m a.s.l., was 0.65 ha. The grower in plot B was offered advice about irrigation, fertilization, and pesticides from the gaiasense system, based on site-specific climatic, soil, and plant nutrition data [39].



(**a**)

(**b**)

Figure 1. (**a**) Map of the study area; (**b**) kiwi orchards (plots A and B).

The climate of the area is typical Mediterranean [40]. Monthly meteorological data of the study area during 2020 and 2021 are shown in Table 1. The soils in both plots are classified as Fluvisols [41]. Soil quality properties of the two plots are summarized in Table 2. Soil textural classification was the same for both plots throughout the soil profile and the majority of the determined chemical properties were also at similar levels. Kiwi trees in both plots were 10 years of age at the beginning of the study. The kiwi cultivar was Tsechelidis in plot B and cv. Hayward in plot A. The vines of cv. Tsechelidis were planted at a spacing of 2 × 5 m, whereas the vines of cv. Hayward at 3 × 3 m. The vines in both sites were trained in a pergola trellis system. Crop harvest was conducted from 25–27 October 2020 and 31 October–1 November 2021 in plot A, whilst in plot B it was on 9 September 2020 and 14 September 2021.

Table 1. Monthly meteorological data of the study area in 2020 and 2021 (Pr: Precipitation; T_{mean}: Mean Temperature; T_{max}: Maximum Temperature; T_{min}: Minimum Temperature; RH_{mean}: Mean Relative Humidity; RH_{max}: Maximum Relative Humidity; RH_{min}: Minimum Relative Humidity; R_s: Solar Radiation; u_2: Wind Speed).

Meteorological Data 2020	Month Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Pr (mm)	3.60	38.70	100.50	192.90	19.50	27.00	4.20	79.50	5.40	39.00	6.60	200.40	717.30
T_{mean} (°C)	4.26	7.93	9.73	12.37	17.80	21.40	23.41	23.43	21.05	16.05	9.97	9.22	14.72
T_{max} (°C)	11.75	14.70	15.99	19.12	25.15	28.08	29.63	29.78	27.89	23.01	16.86	12.81	21.23
T_{min} (°C)	−1.67	1.85	4.15	6.13	10.85	14.89	17.78	18.09	15.34	10.73	4.92	5.85	9.08
RH_{mean} (%)	75.29	74.49	82.25	78.33	75.35	77.68	80.02	82.80	79.02	82.84	86.27	91.25	80.47
RH_{max} (%)	92.57	93.99	97.91	97.70	96.39	96.82	96.23	97.49	95.92	97.79	98.00	98.66	96.62
RH_{min} (%)	48.40	49.93	58.03	51.85	48.94	53.42	58.52	60.56	55.21	58.66	62.77	76.84	56.93
R_s (MJ m^{-2} day^{-1})	8.93	12.09	13.72	18.89	22.65	25.38	26.74	22.14	18.26	12.81	8.09	4.05	16.15
u_2 (m s^{-1})	0.29	0.65	0.30	0.35	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.14
Meteorological Data 2021	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Month Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Pr (mm)	105.60	13.20	54.00	30.00	30.00	21.90	2.70	1.80	0.90	33.30	2.10	57.60	353.10
T_{mean} (°C)	6.87	7.78	8.61	11.84	18.41	21.96	24.58	24.73	19.30	13.06	11.07	5.29	14.46
T_{max} (°C)	11.96	14.07	14.46	18.24	25.51	28.58	30.91	31.19	25.50	17.59	15.40	10.57	20.33
T_{min} (°C)	2.36	2.39	2.71	5.66	11.50	15.73	18.37	18.95	14.27	9.49	7.51	1.11	9.17
RH_{mean} (%)	80.63	78.67	73.51	79.23	76.83	80.28	76.72	79.10	83.50	92.88	94.43	85.48	81.77
RH_{max} (%)	95.21	94.61	92.05	96.53	96.11	96.78	94.27	94.91	96.23	99.30	99.72	97.41	96.09
RH_{min} (%)	59.98	57.05	50.89	55.51	53.15	58.13	53.56	57.62	61.54	78.68	82.79	63.49	61.03
R_s (MJ m^{-2} day^{-1})	7.32	11.58	15.10	18.97	25.65	24.78	26.90	23.15	17.21	11.57	7.25	-	17.22
u_2 (m s^{-1})	0.44	0.40	2.83	0.34	0.03	0.00	0.00	0.00	0.00	0.00	0.03	0.01	0.34

Table 2. Soil quality properties in the two plots (A and B) at the beginning of the growing season. The values shown are averages of two years (S: Sand; Si: Silt; C: Clay; OM: Organic Matter; CEC: Cation Exchange Capacity; EC_e: Electrical Conductivity in the Saturation Paste Extract; ESP: Exchangeable Sodium Percentage; Exchang.: Exchangeable).

Properties	Plot A 0–30 cm	30–60 cm	60–90 cm	Plot B 0–30 cm	30–60 cm	60–90 cm
S (%)	45.1	60.1	77.5	43.5	55.8	57.8
Si (%)	32.8	25.8	14.1	33.5	25.5	25.8
C (%)	22.1	14.1	8.4	23.1	18.7	16.4
Soil texture (USDA)	Loam	Sandy loam	Sandy loam	Loam	Sandy loam	Sandy loam
pH	7.5	7.9	8.1	7.7	7.9	8.0
OM (%)	1.4	0.5	0.3	1.2	0.5	0.3
CEC ($cmol_c$ kg^{-1})	20.6	13.6	8.5	18.6	15.2	12.9
EC_e (dS m^{-1})	0.4	0.7	0.9	0.5	0.7	0.4
ESP	0.9	1.3	1.4	1.0	1.1	1.3
$CaCO_3$ (%)	1.7	4.6	6.6	4.2	11.4	11.3
Olsen P (mg kg^{-1})	24.1	7.5	6.5	23.2	5.7	4.1
Exchang. K (mg kg^{-1})	304.5	98.1	72.3	546.3	206.0	103.0
Exchang. Na (mg kg^{-1})	42.0	35.3	25.0	40.7	39.7	39.7
Exchang. Ca (mg kg^{-1})	3996.4	2630.3	1897.7	2906.4	2836.2	2669.9
Exchang. Mg (mg kg^{-1})	309.3	157.7	107.7	284.4	237.5	137.1

2.2. Irrigation Management

The irrigation system used in both plots was drip irrigation. The same water source was used for the irrigation of both plots. Irrigation water quality characteristics are presented in Table 3. The total amount of irrigation water applied to plot A during the 2020 growing season was 756 mm. During the 2021 growing season, however, it increased to 1350 mm. The total amount of irrigation water applied to plot B was 599 mm and 828.90 mm for the 2020 and 2021 growing seasons, respectively. The higher amounts of irrigation applied to both plots in 2021, compared to 2020, were associated with the lower precipitation during the crop growing season in 2021 (Table 2). The total amount of irrigation water applied to plot B was lower, compared to plot A, in both years of the study. Table A1 presents in detail the irrigation management calendar for both plots.

Table 3. Irrigation water quality parameters in 2020 and 2021.

	pH	$EC_{25\,^\circ C}$ (dS m^{-1})	SAR	NO_3-N (mg L^{-1})
2020	7.7	0.44	0.3	1.7
2021	7.8	0.50	0.3	2.2

2.3. Nitrogen Fertilization Management

Nitrogen fertilizer application to kiwi crops was predominantly carried out through broadcasting and fertigation in both plots. Low amounts of N fertilizer were also added through foliar application. The same fertilizers were used in both plots, however, the amounts and dates of application were different. The total amount of N fertilizer applied to plot A was 231.1 kg N ha^{-1} and 197.2 kg N ha^{-1} in 2020 and 2021, respectively. The total amount of N fertilizer applied to plot B was 150.1 kg N ha^{-1} and 176.3 kg N ha^{-1} in 2020 and 2021, respectively. Plot B received lower N fertilization, compared to plot A, in both years of study. Analytical information about the N fertilization management practices in both plots is summarized in Table 4.

Table 4. Nitrogen fertilization management calendars for both plots under study in 2020 and 2021 (DOY: Day of Year).

Date of Application	DOY	Plot A N Fertilizer (kg ha^{-1})	Method of Application	Date of Application	DOY	Plot B N Fertilizer (kg ha^{-1})	Method of Application
				2020			
8 March	68	96	Broadcasting	10 March	70	96	Broadcasting
17 April	108	44	Broadcasting	15 April	106	17.6	Broadcasting
26 April	117	0.6	Foliar application	25 April	116	0.6	Foliar application
30 May	151	0.2	Foliar application	29 May	150	0.2	Foliar application
10 June	162	18	Broadcasting	6 June	158	16.2	Broadcasting
21 June	173	0.3	Foliar application	18 June	170	0.3	Foliar application
29 June	181	30	Fertigation	25 June	177	8	Fertigation
8 July	190	21	Fertigation	11 July	193	6	Fertigation
21 July	203	21	Fertigation	18 July	200	6	Fertigation
				2021			
9 March	68	33	Broadcasting	10 March	69	38.5	Broadcasting
5 April	95	0.3	Foliar application	3 April	93	0.3	Foliar application
20 April	110	56	Broadcasting	22 April	112	53.2	Broadcasting
28 April	118	0.3	Foliar application	29 April	119	0.3	Foliar application
8 May	128	0.2	Foliar application	11 May	131	0.2	Foliar application
18 May	138	0.3	Foliar application	23 May	143	0.3	Foliar application
4 June	155	56	Broadcasting	6 June	157	49	Broadcasting
14 June	165	0.2	Foliar application	16 June	167	0.2	Foliar application
3 July	184	30	Fertigation	28 June	179	26	Fertigation
18 July	199	21	Fertigation	5 July	186	8	Fertigation

2.4. Field Measurements and Analysis

Each year, in each plot, soil samples were collected in triplicate, three times in the crop growing season; namely on 12 May 2020 (samples taken from both plots), 16 July 2020 (both plots), 23 September 2020 (plot B), 31 October 2020 (plot A), 26 February 2021 (both plots), 16 July 2021 (both plots), 10 September 2021 (plot B), and 01 November 2021 (plot A). The reason why the third sample was collected on different dates for each plot is associated with the different harvest dates in each plot as already mentioned in Section 2.1.

Soil samples were collected with a soil sampler at three soil depths (0–30 cm, 30–60 cm, 60–90 cm), placed in polyethylene bags, and transferred to the laboratory for soil analysis. The received soil samples were air-dried at room temperature (20–25 °C), gently crushed, and passed through a 2 mm sieve to be used for analysis. Soil samples were analyzed for nitrate (NO_3) and ammonium (NH_4) nitrogen. Both NO_3 and NH_4 ions available in soil were extracted with 2 M KCl and they were measured using UV–Vis spectrometry and the sodium salicylate–sodium nitroprusside method, respectively [42,43]. Annual yield data were provided by the grower of each plot.

2.5. Model Description and Calibration

2.5.1. Model Description

Crop growth simulation model CropSyst was used to simulate kiwi yield and N budget. CropSyst simulates the soil–water budget, soil–plant N budget, crop phenology, canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and salinity [36]. These processes are affected by weather, soil characteristics, crop characteristics, and cropping system management options including, among others, irrigation and N fertilization. The model has been evaluated in many locations around the world by comparing model estimates to data collected in field experiments [36].

The mineral N budget in the CropSyst model includes separate budgets for nitrate and ammonium and the processes used are N transport, N transformations, ammonium sorption, crop N uptake, and residue mineralization. The method developed for CropSyst for N transport through the soil profile is similar to that described by Corwin et al. [44]. The N transformations developed for CropSyst include net mineralization, nitrification, and denitrification, which follow the approach presented by Stöckle and Campbell [45] using first order kinetics and are assumed to occur in the top 30 to 50 cm of the soil profile. Crop N uptake was modeled by modifying the approach of Godwin and Jones [46] where N uptake is determined as the minimum of crop N demand and potential N uptake. Crop N demand is the amount of N the crop needs to meet its potential growth, as limited by light, temperature, and water, plus its deficiency demand. Yield simulation depends on total biomass accumulated at physiological maturity (B_{PM}) and the harvest index (HI = harvestable yield/aboveground biomass) [36]. The harvest index is determined using as a base an unstressed harvest index modified according to stress intensity (water and N) and crop sensitivity to stress during flowering and grain filling.

2.5.2. CropSyst Calibration, Validation, and Evaluation

Although the model leads to improved decision making in fertilization and water management, it needs to be calibrated and validated through specific field experiments to be used in certain areas. In our study, two-year field data were used for model parameterization. CropSyst was calibrated for one year and then validated for the other year, separately for each plot. The parameters calibrated by the model include crop as well as soil parameters. During calibration, the difference between the simulation and observation result was minimized by a trial-and-error approach. After calibration, the model was validated by applying the calibrated set of parameters to the other year for plot A and plot B.

The evaluation of the CropSyst model was performed by comparing the observed and simulated values of yield and soil inorganic N (0–90 cm depths) over the growing season. Specifically, the model's simulation performance was evaluated using the statistical criteria (Equations (1)–(5)) of the mean absolute error (MAE), the mean absolute percentage error (MAPE), the percent bias (PBIAS), the root mean square error (RMSE), and the normalized root mean square error (NRMSE). Mean absolute error (MAE) indicates the average magnitude of the errors in observed and simulated values, without considering their direction, while mean absolute percentage error (MAPE) measures the size of the error in percentage terms. The percent bias (PBIAS) measures the average tendency of the simulated values to be larger or smaller than their observed ones. The optimal value is zero, with low-magnitude values indicating accurate model simulation. Positive values of PBIAS indicate overestimation bias whereas negative values indicate model underestimation bias. The root mean square error (RMSE) expresses the variance of errors and ranges from zero to positive infinity, with the model's performance improving as it approaches zero. The normalized root mean square error (NRMSE) can be interpreted as a fraction of the overall range that is typically resolved by the model with values between zero and one.

$$\mathrm{MAE} = \frac{\sum_{i=1}^{n} |O_i - S_i|}{n} \tag{1}$$

$$\mathrm{MAPE} = \frac{\sum_{i=1}^{n} \frac{|O_i - S_i|}{O_i}}{n} \times 100 \tag{2}$$

$$\mathrm{PBIAS} = \frac{\sum_{i=1}^{n} (S_i - O_i)}{\sum_{i=1}^{n} O_i} \times 100 \tag{3}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (O_i - S_i)^2}{n}} \tag{4}$$

$$\mathrm{NRMSE} = \frac{\mathrm{RMSE}}{\overline{O}} \tag{5}$$

where: n is the number of observations, $\overline{O}$ is the mean of the observations, S_i and O_i are the simulated and observed values, respectively.

2.6. Environmental Performance Indicators

To assess the environmental consequences of the different irrigation and N fertilization management practices in kiwi production, the following agri-environmental indicators were evaluated for the two plots. Agri-environmental indicators provide information on environmental as well as agronomic performance [47,48].

2.6.1. Nitrogen Budget Components (%TAN)

Nitrogen budget components as a percentage of total available soil nitrogen (% TAN) express the outputs of N budget, namely N uptake, N leached, and N lost in the atmosphere, and also the residual soil N, as a percentage of the total available nitrogen (TAN) in the soil profile. Total available nitrogen (TAN) (kg N ha^{-1}) was calculated as the sum of total inorganic N applied as fertilizer (F_N), the initial inorganic N in the soil profile (0–90 cm) (S_N), and the net mineralized N (N_{min}) (Equation (6)).

$$\mathrm{TAN} = F_N + S_N + \text{net } N_{min} \tag{6}$$

The net mineralized N was estimated as the difference between the mineralized N and the immobilized N during the crop growing season and was simulated by the CropSyst model. N uptake (kg N ha^{-1}) was simulated by the CropSyst model and refers to crop N removal. N environmental losses by leaching (leached N), nitrification, denitrification, and volatilization (N_2O losses and N gaseous losses) during the crop growing season were also simulated by the CropSyst model in kg N ha^{-1}.

2.6.2. Residual Soil Nitrogen (kg N ha^{-1})

Residual soil nitrogen (RSN) shows the amount of inorganic N (ammonium and nitrate) that remains in the soil at the end of the growing season after crops have been harvested, for the 0–90 cm depths.

2.6.3. Nitrogen Productivity Factor (kg N Mg^{-1})

Nitrogen productivity factor (NPF) was calculated as the amount of N fertilizer applied per unit of yield (Equation (7)).

$$\mathrm{NPF} = \frac{F_N}{Y_s} \tag{7}$$

where: Y_s is the simulated yield of kiwi crop (Mg ha^{-1}) and F_N is the amount of N fertilizer applied (kg N ha^{-1}).

2.6.4. Irrigation Water Productivity (m^3 Mg^{-1})

Irrigation water productivity (IWP) was determined as the simulated yield obtained per unit of irrigation water applied (kg m^{-3}) (Equation (8)) and is an index of water use efficiency by the crop. This indicator considers just the total amount of water applied by irrigation, or irrigation water use (IWU), with no distinction of what part is consumed as ET_c, LF, or N-BWU. ET_c is the crop evapotranspiration and LF is the leaching fraction, which must be considered when there is a risk of salt accumulation in the root zone. N-BWU is the non-beneficial water use, i.e., the water that is lost through percolation, runoff out of the cropping site, and wind drift when sprinkling irrigation is applied.

$$\mathrm{IWP} = \frac{Y_s}{\mathrm{IWU}} \tag{8}$$

where: Y_s is the simulated crop yield (10^3 kg ha^{-1}) and IWU is the total amount of the applied irrigation water (m^3 ha^{-1}). This equation, however, has the limitation of not considering the effect of precipitation on crop performance.

2.6.5. Estimation of Environmental Performance

The environmental performance of kiwi production was evaluated, based on the above agri-environmental indicators estimated for the two kiwi orchards under study, taking into consideration the different irrigation and N fertilization management practices applied to each orchard. Figure 2 shows a flowchart that summarizes the approach for the environmental performance evaluation. As presented in Figure 2, the input data for the elaboration of the CropSyst model included meteorological data, soil properties, crop parameters, management practices, and the required initial conditions. Following model calibration and validation for crop yield and soil inorganic N for 2020 and 2021 growing seasons, N budget was simulated (including soil inorganic N, N uptake, leached N, and N lost to the atmosphere). Based on N budget simulation results, agri-environmental indicators were estimated and the environmental effects of the different irrigation and N fertilization management practices applied to kiwi orchards were evaluated.

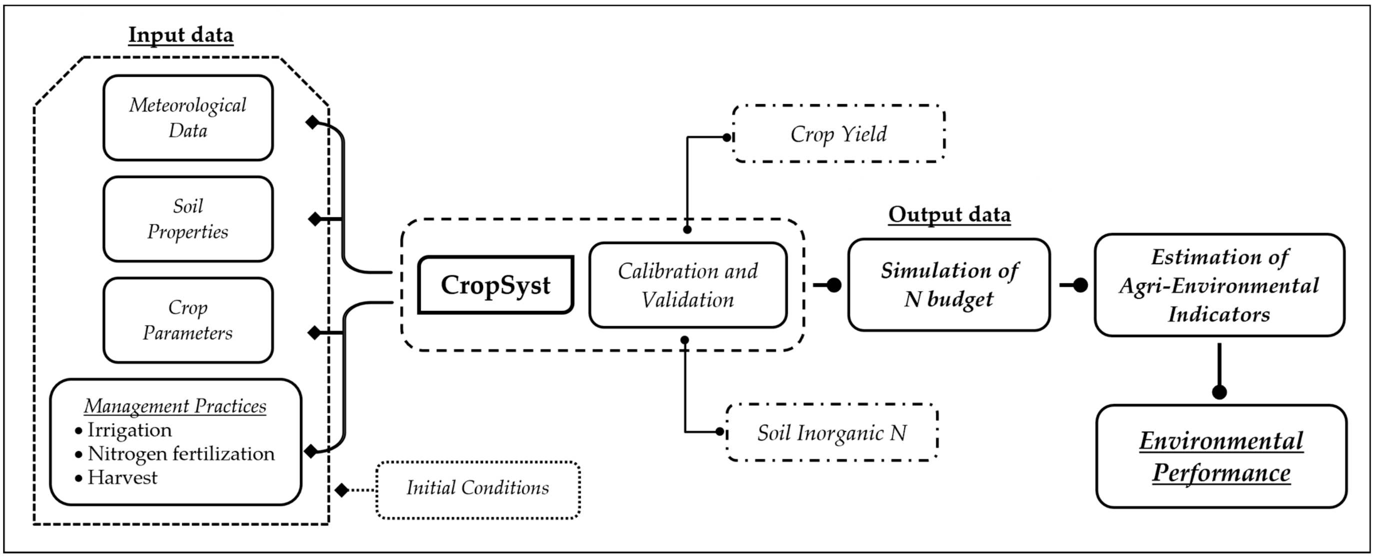
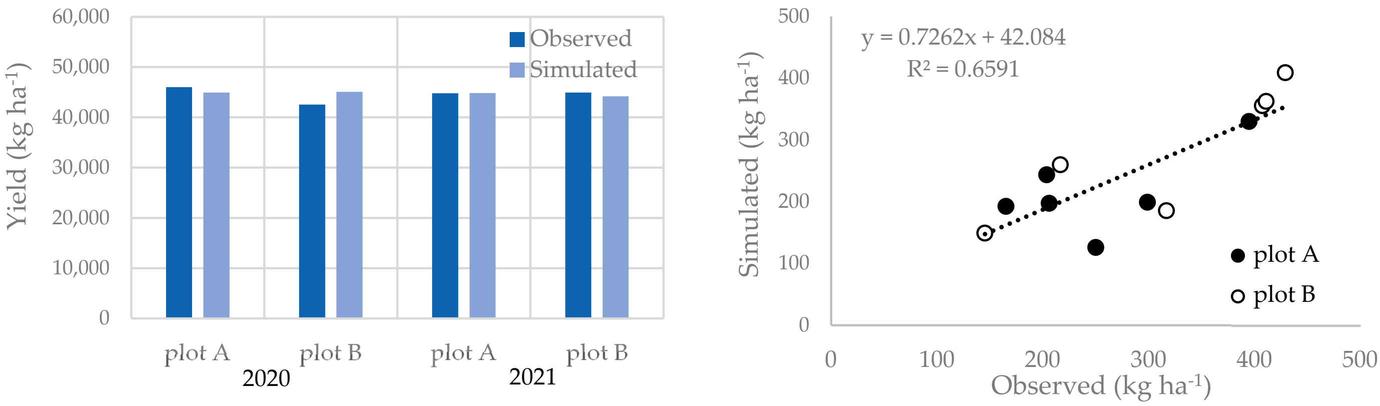


Figure 2. Flowchart of the methodology used to estimate the environmental performance of the different irrigation and N fertilization management practices in kiwi production in the present study, using CropSyst model and agri-environmental indicators.

3. Results and Discussion

3.1. Model Performance

The observed and simulated yields by the CropSyst model for the two plots for the years 2020 and 2021 are shown in Figure 3a while in Figure 3b the comparison of observed and simulated soil inorganic N within the 0–90 cm depths in 2020 and 2021 is presented. The statistical criteria for the model evaluation in simulating yield and inorganic N are shown in Table 5.



(**a**) Observed and Simulated Yield (**b**) Observed and Simulated Soil Inorganic N

Figure 3. (**a**) Observed and simulated yield (kg ha^{-1}) for the two plots (A and B) in 2020 and 2021; (**b**) comparison of observed and simulated soil inorganic N (sum of NH_4-N and NO_3-N) within the 0–90 cm depths in 2020 and 2021.

Table 5. Statistical comparison between the observed and simulated yield and soil inorganic N (sum of NH_4-N and NO_3-N) within the 0–90 cm depths in 2020 and 2021.

Evaluated Parameters	Statistical Criteria				
	MAE [1]	MAPE [2]	PBIAS [2]	RMSE [1]	NRMSE
Yield	108	2.50	0.41	1422.96	0.03
Soil inorganic N	55.45	19.44	−13	68.87	0.24

MAE: mean absolute error; MAPE: mean absolute percentage error; PBIAS: percent bias; RMSE: root mean square error; NRMSE: normalized root mean square error; [1]: kg ha^{-1}; [2]: %.

The comparison between the observed and simulated yields illustrated a good agreement between measured and predicted values by the CropSyst model, as a low percentage of difference between observed and simulated values existed (Table 5). The mean absolute percentage error (MAPE) was low, showing the model's highly accurate prediction, with the mean absolute error (MAE) being 108 kg ha^{-1}. The value of percent bias (PBIAS) is close to zero, indicating very good performance of the model in yield simulation. The root mean square error (RMSE) was 1422.96 kg ha^{-1} and normalized root mean square error (NRMSE) was close to zero, showing the very good performance of the model.

The simulation of soil inorganic N (0–90 cm depths) compared relatively well with the measured data. R^2 (Pearson's correlation coefficient) describes the proportion of the variance in observed data explained by the model with values greater than 0.5 being considered acceptable (R^2 = 0.6591). Mean absolute percentage error was 19.44%, indicating a good prediction by the model. The model had a mean absolute error of 55.45 kg N ha^{-1}. This value, although it is not negligible, constitutes only 5.2% of the mean TAN and therefore was considered acceptable. RMSE value was 68.87 kg N ha^{-1} and NRMSE was 0.24, showing a relatively good performance by the CropSyst model. PBIAS had a negative low value indicating the model's good performance and underestimation of soil inorganic N.

3.2. Simulation of N Budget

3.2.1. Soil Inorganic N

Simulated inorganic N (sum of NH_4-N and NO_3-N) fluctuation within the soil profile (0–90 cm depths) on a daily basis for both plots and years of study is presented in Figure 4. The pattern of inorganic N fluctuation differed between the plots and the years mainly due to the different irrigation and fertilization management practices and weather conditions (from year to year). Inorganic N content was high at the beginning of the 2020 growing season in both plots (655 kg N ha^{-1} and 477 kg N ha^{-1} in the top 90 cm in plots A and B, respectively). Other studies in medium-textured soils in the Mediterranean region have also found similarly high values. Villar-Mill et al. [49] reported a range of 123 to 459 kg NO_3-N ha^{-1} in the top 120 cm, Vazquez et al. [50] reported 851 kg inorganic N ha^{-1} in the top 100 cm, and Vazquez et al. [51] reported 453 kg inorganic N ha^{-1} in the top 100 cm. During the growing season, soil inorganic N presented a decreasing trend; the residual soil inorganic N was up to 70% lower in relation to the initial N, suggesting potential N leaching losses. In the 2021 cultivation period, the initial soil inorganic N was at lower levels compared with 2020 (206 kg N ha^{-1} and 145 kg N ha^{-1} in the top 90 cm in plots A and B, respectively).

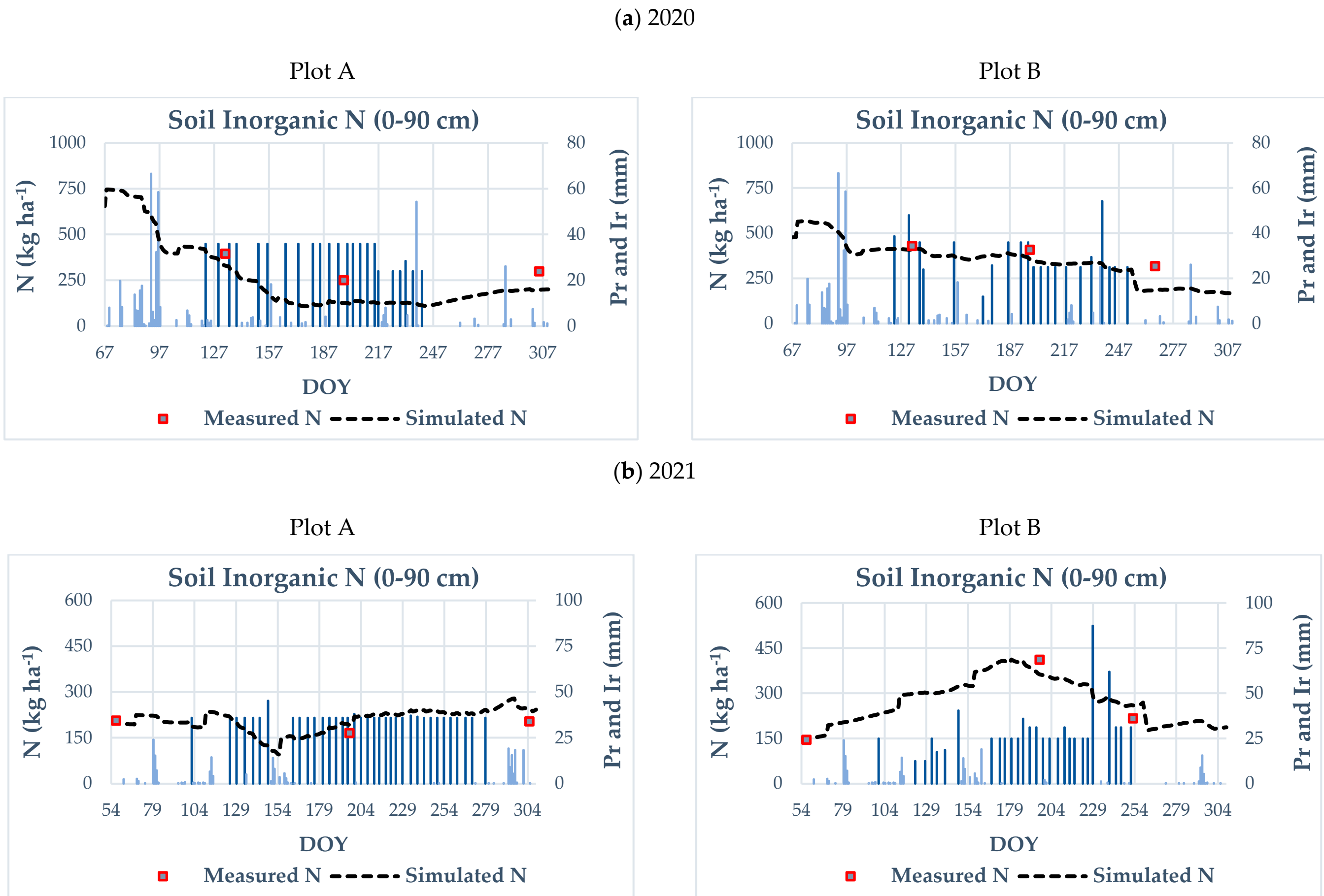


Figure 4. Soil inorganic N (sum of NH_4-N and NO_3-N) within the 0–90 cm depths, for plots A and B in (**a**) 2020 and (**b**) 2021; observed and simulated values by the CropSyst model. The blue bars show precipitation (Pr), whereas the dark blue bars show irrigation (Ir) water applied.

3.2.2. N Leaching Losses

The inorganic N leached (sum of NH_4-N and NO_3-N) below the 90 cm depths on a daily basis, as simulated by CropSyst model, for plots A and B in both years of study is shown in Figure 5. In 2020, for both plots under study, high daily N leaching rates (maximum up to 57.5 kg N ha^{-1} day^{-1} and 29.6 kg N ha^{-1} day^{-1} for plots A and B, respectively) occurred early in the growing season, following the application of the first dose of N fertilizer and about a 2-week period of rainfall (including three rainfall events of 66.6, 32.4, and 58.5 mm day^{-1} towards the end of this 2-week period). Despite the high soil inorganic N content in the profile at the beginning of the growing season, the growers of both plots applied the basic N fertilizer dose (96 kg N ha^{-1}, Table 4) according to the standard practices in the area. This management practice, in conjunction with the weather conditions, most probably resulted in the high N leaching rates. Towards the end of the growing season, daily N leaching rates were very low. Other studies have already shown the dependency of N leaching on both the total amount of precipitation and its distribution throughout the year [10,13]. The daily N leaching pattern in 2021 was very different compared to 2020, mostly due to the different weather conditions, irrigation, and N fertilizer application. In 2021, the daily N leaching pattern also differed between the two plots. This could be mainly attributed to the different N fertilizer and irrigation management practices. Maximum daily N leaching rate was 23.8 kg N ha^{-1} day^{-1} and 39.4 kg N ha^{-1} day^{-1} for plots A and B, respectively.

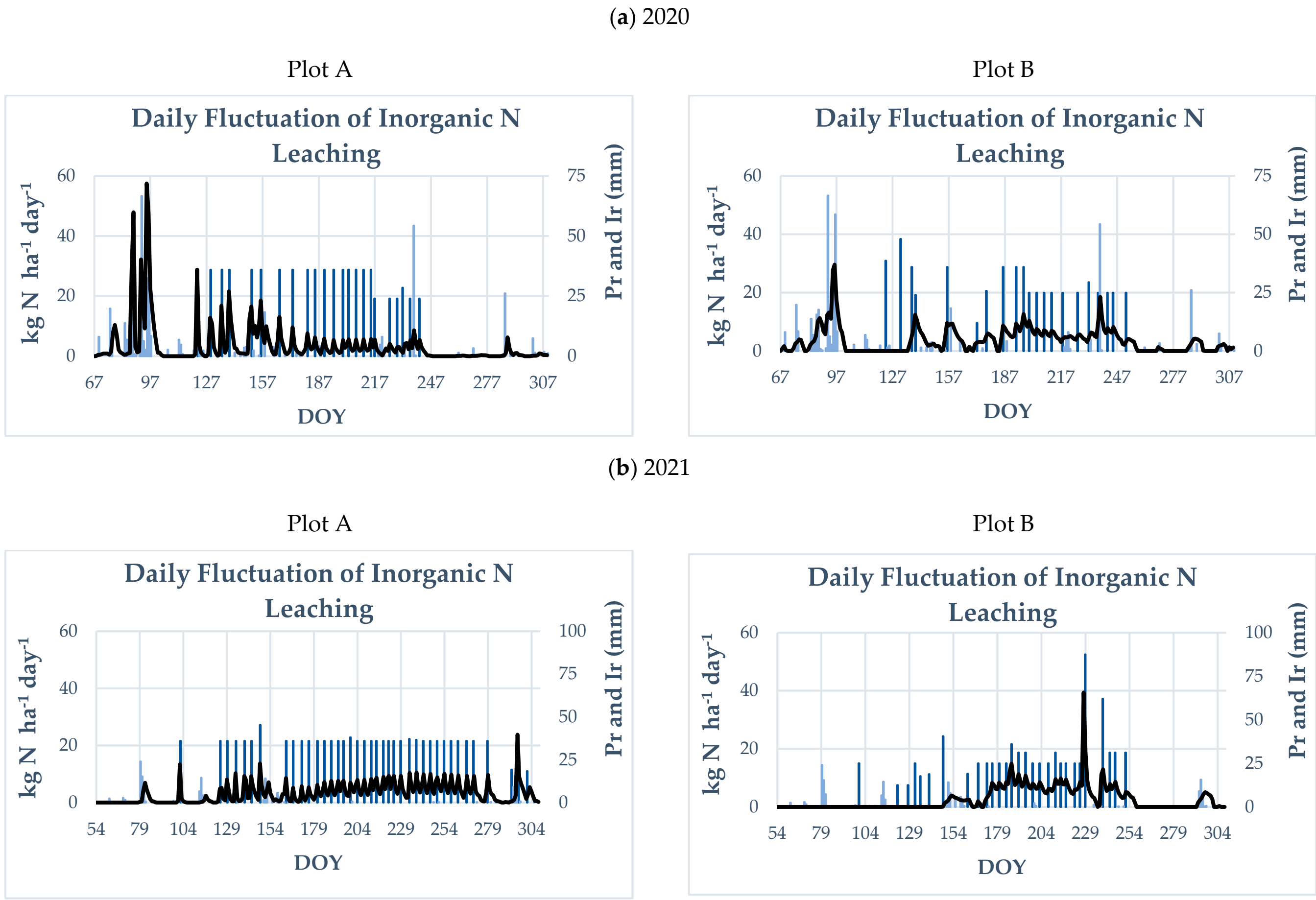


Figure 5. Daily fluctuation of inorganic N (sum of NH_4-N and NO_3-N) leaching in g N ha^{-1} day^{-1}, for plots A and B in (**a**) 2020 and (**b**) 2021; simulated by the CropSyst model. The blue bars show precipitation (Pr), whereas the dark blue bars show irrigation (Ir) water applied.

3.2.3. Atmospheric N Losses

A large number of peaks of simulated daily nitrous oxide (N_2O) emissions were detected during 2020 and 2021 concerning both plots (Figure 6). The large number of peaks are a result of the combination of many fertilizer applications and irrigation events during the cultivation periods (Tables 4 and A1). During 2020, the largest N_2O peak, being observed about four months after the first application, was 70 g N_2O-N ha^{-1} day^{-1} regarding plot A and 110 g N_2O-N ha^{-1} day^{-1} in the case of plot B. In 2021, daily emissions were larger compared to 2020, reaching about 170 g N_2O-N ha^{-1} day^{-1} and 150 g N_2O-N ha^{-1} day^{-1} in plots A and B, respectively. The increase in daily N_2O emissions in 2021 may be predominantly associated with the increased amount of irrigation water applied, compared to 2020.

In both plots and years of study, N gaseous losses were predominantly associated with N fertilizer application with the method of broadcasting. As shown in Figure 7, regarding plot A, the largest peak of gaseous N losses was 4.86 kg N ha^{-1} day^{-1} in 2020 and 3.51 kg N ha^{-1} day^{-1} in 2021. In the case of plot B, the largest peak of gaseous N losses was 8.08 kg N ha^{-1} day^{-1} in 2020 and 7.24 kg N ha^{-1} day^{-1} in 2021. All peaks, in both plots, corresponded to the highest amount of N fertilizer applied by broadcasting early in the growing season (see Table 4).

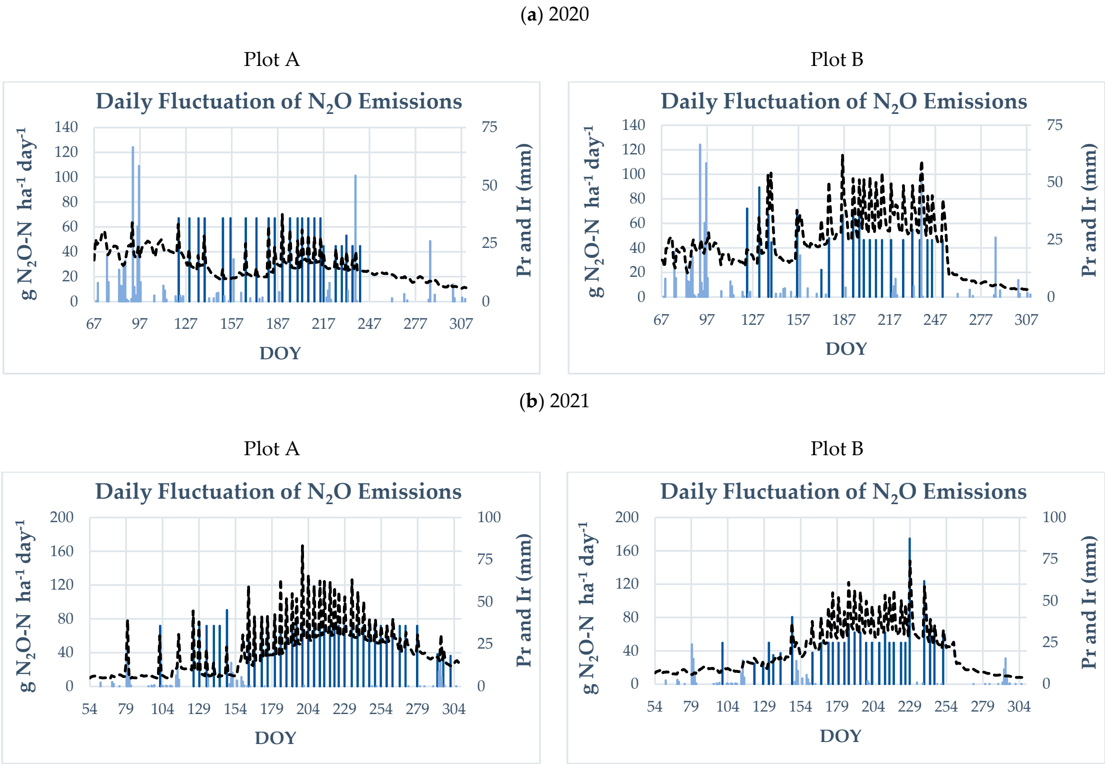


Figure 6. Daily fluctuation of nitrous oxide emissions in g N_2O-N ha^{-1} day^{-1}, for plots A and B in (**a**) 2020 and (**b**) 2021; simulated by the CropSyst model. The blue bars show precipitation (Pr), whereas the dark blue bars show irrigation (Ir) water applied.

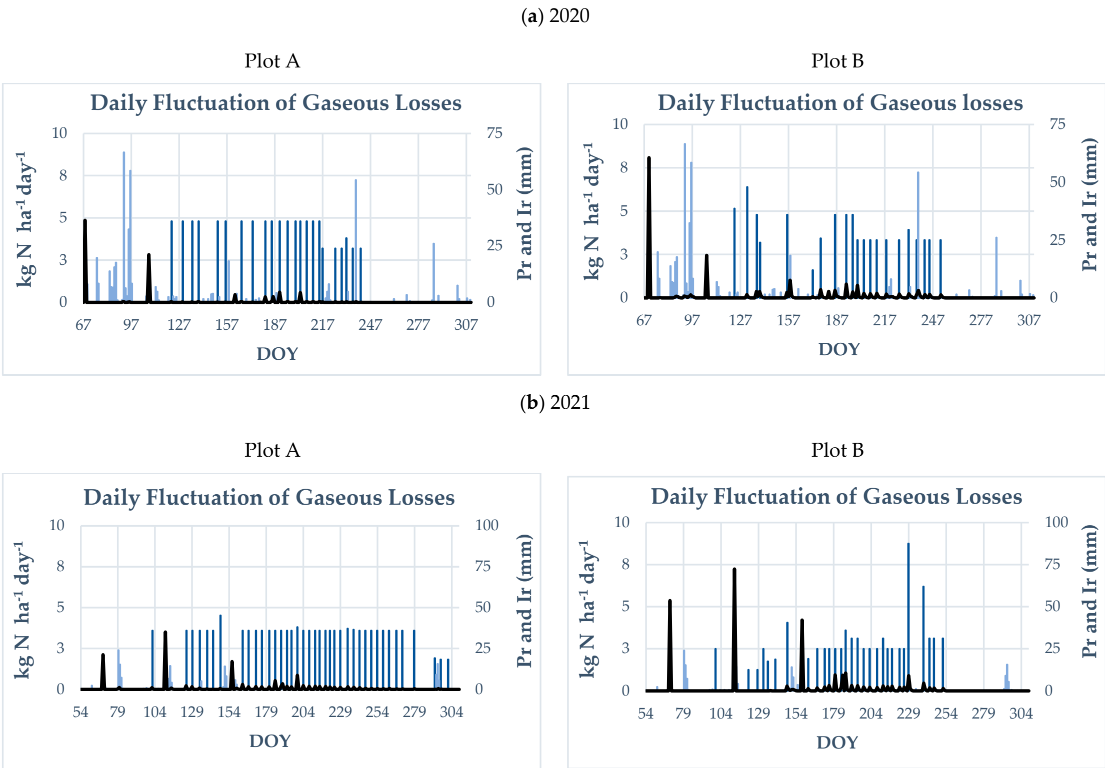


Figure 7. Daily fluctuation of gaseous losses in kg N ha^{-1} day^{-1}, for plots A and B in (**a**) 2020 and (**b**) 2021; simulated by the CropSyst model. The blue bars show precipitation (Pr), whereas the dark blue bars show irrigation (Ir) water applied.

3.2.4. Kiwi N Uptake

Simulated kiwi N uptake was comparable for both plots in both years of study. Mean N uptake was 103.3 kg ha^{-1} (it ranged between 102.8 and 103.7 kg N ha^{-1} between the different plots and years of study).

3.3. Environmental Performance: Agri-Environmental Indicators

Agri-environmental indicators were calculated based on the N budget simulation results to assess the environmental consequences (focusing on N losses) of the different irrigation and N fertilization management practices in kiwi production. Figure 8 illustrates the arithmetic mean of the outputs of N budget, namely N uptake, leached N, and N lost in the atmosphere (N_2O and gaseous loss), and also the residual soil N, as percentage of the total available nitrogen (TAN) in the soil profile, based on CropSyst simulation results, for the 2020 and 2021 growing seasons. N leaching losses were higher in plot A in relation to plot B, indicating higher environmental threat to groundwater quality during the cultivation periods. A slightly higher percentage of residual N was observed in the case of plot A, while N uptake and N atmospheric losses were lower compared to plot B. The emission factor (EF) for direct N_2O losses from both plots was within the IPCC EF_1 uncertainty range of 0.3–3% [52]. N losses (sum of atmospheric and N leaching losses) were up to 73.3% of TAN. Other research has illustrated that N losses to the environment accounted for 77.2% of total N input in kiwi orchards in China [53] and 76% of N fertilizer inputs in olive groves in Portugal [54]. In absolute values, N losses were 866.8 kg N ha^{-1} and 786.1 kg N ha^{-1} for plots A and B, respectively; hence, an increase of about 10% in N losses was found for plot A compared to plot B. The management practices in plot B involved lower application of both irrigation water and N fertilizer (by 32.2% and 23.8%, respectively, considering the total amount applied in both years in plot A). Consequently, the reduced irrigation and N fertilization resulted in lower N losses, whilst crop yield and N uptake were similar for both plots.

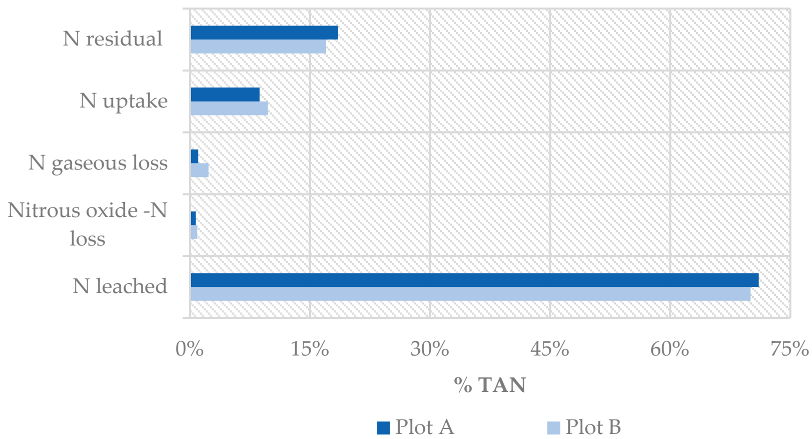


Figure 8. Mean values of crop N uptake, residual soil N (0–90 cm), leached N, and N lost to the atmosphere (N_2O loss and N gaseous loss), as percentage of total available soil N (TAN) for the plots A and B.

Mean N leaching losses were 845.86 and 752.28 kg N ha^{-1}, for plots A and B, respectively. Other research work in drip-irrigated crops in the Mediterranean region has shown nitrate N leaching losses ranging from 431 to 891 kg NO_3-N ha^{-1} [50]. Mean N leaching losses expressed as a percentage of TAN (Figure 8) were higher than 70% in both plots. This high percentage of TAN leached below the 90 cm depths during the crop growing season, hence influencing groundwater quality. Kiwifruit vines have a relatively shallow rooting system, with the critical root zone distributed within the top 60 cm depths [55]. Consequently, more than 70% of TAN, which leached below the root zone, could not be used by kiwi and contributed to groundwater pollution. Therefore, kiwi production posed a severe threat to the environment in both orchards under study and management practices need to be improved. Gao et al. [56], in their study, showed that more than 77.5% of nitrate leached below the root zone in kiwi orchards in China. Optimizing water and fertilizer management practices appears to be the primary approach for reducing N leaching [57].

Mean residual soil N was lower in plot B compared to plot A (Table 6), thus indicating the lower potential risk for N leaching following the growing season in plot B in relation to plot A. The lower residual N in plot B may be attributed to the lower N fertilizer applied. Other research has also shown that nitrate N accumulation in soil increased with increasing N application rates [10,57,58].

Table 6. Mean values of Residual Soil Nitrogen (RSN), Nitrogen Productivity Factor (NPF), and Irrigation Water Productivity (IWP) for plots A and B.

	RSN (kg N ha^{-1})	NPF (kg N Mg^{-1})	IWP (kg m^{-3})
Plot A	220	4.8	4.6
Plot B	181	3.7	6.4

NPF was lower in plot B compared to plot A (Table 6) because of the lower N fertilizer addition per Mg of product, suggesting the better N use efficiency in plot B. According to Koukoulakis and Papadopoulos [59], N removal by kiwifruit harvest is 120 kg N ha^{-1} for a yield of 30 Mg ha^{-1}, suggesting an average N removal rate by the crop of 4 kg N Mg^{-1} of product. This value is in good agreement with the calculated NPF, especially in the case of plot B.

The amounts of N fertilizer applied by the growers in the two plots under study ranged from about 150 to 230 kg N ha^{-1}. These amounts of N fertilizer may fully cover or be in excess of crop requirements, as kiwifruit require approximately 150 kg N ha^{-1} year^{-1} [8]. Soil inorganic N constitutes a source of available N for plant uptake and should be taken into consideration to optimize N fertilization. As already shown in Figure 4, the soil inorganic N content in the profile was not negligible in both plots and years of study, suggesting that the amount of N fertilizer applied was higher than necessary. Over-fertilization with N results in N surplus causing large amounts of residual inorganic N in soil [13,58] which can be easily leached into deep soil layers, resulting in negative environmental impacts [14,60].

Finally, IWP was higher in plot B compared to plot A (Table 6), suggesting higher kiwifruit production per m^3 of irrigation water applied, hence demonstrating the better water use efficiency by kiwi in plot B. Both plots, however, were over-irrigated. Irrigation water needs (IrN) of kiwi crops were estimated (not simulated) on a monthly basis as the difference between crop evapotranspiration (ET_c), calculated according to Allen et al. [61], and effective precipitation (P_e), determined according to the USDA [62] (Table 7). As shown in Table 7, in most cases, the amount of irrigation water applied to both plots was higher than crop irrigation water needs; higher than double the needs in certain months. The excessive amount of irrigation water applied, apart from causing waste of resources, potentially increased drainage and consequently N leaching. Other studies have shown increased nitrate leaching with increased irrigation [59,60,63].

Table 7. Monthly kiwi Evapotranspiration (ET_c) in mm, Effective Precipitation (P_e) in mm, Irrigation water Needs (IrN) in mm (IrN = $ET_c - P_e$), and Irrigation water applied (Ir) in mm, for plots A and B during the 2020 and 2021 growing seasons.

	Plot A				Plot B			
	ET_c	P_e	IrN	Ir	ET_c	P_e	IrN	Ir
				2020				
March	21	100	−80		21	100	−80	
April	37	122	−85		46	122	−76	
May	93	20	73	180	99	20	79	144
June	138	27	111	144	138	27	111	72

Table 7. *Cont.*

	Plot A				Plot B			
	ET_c	P_e	IrN	Ir	ET_c	P_e	IrN	Ir
				2020				
July	156	4	152	252	156	4	152	208
August	127	77	50	180	127	77	50	125
September	88	5	83		33	0	33	50
October	41	30	11					
Total			481	756			426	599
				2021				
March	29	54	−25		29	54	−25	
April	37	30	7	36	46	30	16	25
May	94	30	64	216	100	30	70	112
June	140	22	118	180	140	22	118	119
July	159	3	156	288	159	3	156	230
August	131	2	129	288	131	2	129	281
September	83	1	82	252	49	1	48	62
October	47	33	14	90				
Total			571	1350			538	829

The above results clearly present that kiwifruit was over-irrigated and over-fertilized with N in the area. The over-irrigation and over-fertilization with N occurred in both orchards under study and may explain the high percentage of TAN leached below the 90 cm depths during the crop growing season.

4. Conclusions

The CropSyst model was calibrated and validated with field measurements in two kiwi orchards in northern Greece during two consecutive growing seasons. According to CropSyst model simulation results, the simultaneous reduction in N fertilizer and irrigation water inputs to kiwi production resulted in similar yields and N uptake, but lower N leaching losses during the crop growing season. Additionally, it resulted in lower RSN and hence lower potential risk for N leaching following the cultivation period and lower NPF and IWP, indicating better N and water use efficiency. More than 70% of total available N leached below the 90 cm depths during the crop growing season in both study sites, due to over-irrigation and over-fertilization with N, posing a potential threat to groundwater quality.

This study has pointed out the necessity for improved irrigation and N fertilizer management for sustainable kiwi production in the area. Further work is necessary to determine the optimal N fertilizer and irrigation water management strategies.

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Data Availability Statement: The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Irrigation management calendars for plots A and B in 2020 and 2021.

Irrigation Management Practices 2020				Irrigation Management Practices 2021			
Plot A		Plot B		Plot A		Plot B	
Date of Application	**Irrigation (mm)**	**Date of Application**	**Irrigation (mm)**	**Date of Application**	**Irrigation (mm)**	**Date of Application**	**Irrigation (mm)**
1 May	36	2 May	36	11 April	36	9 April	25
8 May	36	10 May	48	4 May	36	1 May	12.5
14 May	36	16 May	36	8 May	36	7 May	12.5
18 May	36	18 May	24	13 May	36	11 May	25
30 May	36	4 June	36	18 May	36	14 May	12.5
4 June	36	20 June	12	22 May	36	19 May	18.75
14 June	36	25 June	24	27 May	36	27 May	31.2
21 June	36	4 July	36	11 June	36	10 June	18.75
29 June	36	11 July	36	15 June	36	16 June	25
3 July	36	15 July	36	20 June	36	21 June	25
8 July	36	18 July	25	24 June	36	24 June	25
13 July	36	22 July	25	29 June	36	28 June	25
18 July	36	26 July	25	3 July	36	2 July	25
21 July	36	30 July	25	7 July	36	5 July	36
25 July	36	5 August	25	11 July	36	9 July	31.2
29 July	36	13 August	25	14 July	36	13 July	31.2
2 August	36	19 August	25	18 July	36	17 July	25
4 August	24	24 August	25	22 July	36	21 July	25
12 August	24	29 August	25	26 July	36	26July	25
16 August	24	1 September	25	30 July	36	30 July	31.2
19-August	24	8 September	25	2 August	36	2 August	25
23 August	24			6 August	36	5 August	25
28 August	24			9 August	36	10 August	25
				12 August	36	13 August	25
				16 August	36	16 August	87.5
				21 August	36	26 August	62
				25 August	36	30 August	31.2
				29 August	36	2 September	31.2
				2 September	36	8 September	31.2
				6 September	36		
				10 September	36		
				14 September	36		
				18 September	36		
				23 September	36		
				27 September	36		
				5 October	36		
				19 October	18		
				23 October	18		
				28 October	18		

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