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Integrated Modelling Approaches for Sustainable Agri-Economic Growth and Environmental Improvement: Examples from Greece, Canada and Ireland

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Abstract: Complex agricultural problems concern many countries, as a result of competing economic and environmental objectives. In this work we model three common agricultural problems through optimization techniques: a water-scarce area with overexploited surface and groundwater resources due to over-pumping for irrigation (Greece); an area facing water quality deterioration caused by agriculture (Canada); and an intensified animal farming area facing environmental degradation and increased greenhouse gases emissions (Ireland). Multiple goals are considered to optimize farmers' welfare and environmental sustainability. The proposed approaches are new applications for each case-study, providing useful insights for most countries facing similar problems.

Keywords: optimization; linear programming; non-linear programming; goal programming; water management; agriculture

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1. Introduction

Agriculture is a human activity that has had a significant impact on the development of societies, but these benefits have come with a cost for the environment. Addressing these conflicting economic and environmental objectives has become increasingly topical [1]. Agriculture makes use of environmental resources (e.g., soil, water, nutrients), is responsible for the emission of harmful substances (e.g., fertilizers, pesticides, greenhouse gases—GHGs), yet societies have production expectations (yields, production, profits). The optimal way to cover the economic demand and achieve environmental sustainability through the most efficient use of resources and emissions' control is a challenging multi-objective problem that requires integrated approaches to balance those, often conflicting, objectives [2].

One commonly studied problem is water quality deterioration from agricultural sources. Nitrogen (N) and phosphorus (P) runoffs from crop production are major concerns for many countries [3]. Intensive livestock production is also a significant source of nutrients' discharge, water bodies' pollution, or greenhouse gases emissions [4]. Management models based on environmental simulations, using scenario analysis and/or Best Management Practices (BMPs) or Decision-Support-Systems (DSS) are widely used to evaluate the different alternatives [5]. The methods to control or treat non-point pollution refer to source control, process control, or end treatment, where the literature is vast; however, there are fewer efforts to minimize pollution by integrating the farmers' perspective (e.g., ensuring the same or higher profits to the farmers) [3,6].

Water quantity management and allocation is another typical problem linking environmental sustainability and the economic activities of different users [5,7]. Studying and optimizing the distribution of water volume over time and space has become a multifactorial problem to support integrated decision-making [8,9]. Analyzing water quality, quantity, economic and social aspects together is more challenging in terms of conceptualization, data, modelling, evaluating alternative options, and reaching agreements [10,11].

This work aims to build on that direction and encourage similar efforts; namely, the practice of addressing common concerns successfully in different environments, analyzing water quality, quantity management, and socio-economic aspects through optimization techniques. Despite the complex and data-hungry nature of integrated models, which has been the main limitation and impediment to their practical application so far, such models provide useful insights [12]. Based on experiences from different case studies, three separate representative problems are presented, analyzing the issues mentioned above: a dry Mediterranean watershed in Central Greece with overexploited surface and groundwater resources due to the intensified agriculture; a typical northern watershed in Ontario, Canada, facing water quality issues from agricultural runoff; and an Irish watershed where the expanding livestock farming deteriorates water quality.

The role of the proposed optimization models is to balance conflicting objectives and propose a more integrated and sustainable planning approach. The contribution of this paper relies on proposing new modelling descriptions for the study areas examined that address these objectives for widespread water-related problems faced by the agriculture sector. The use of models based on standard optimization techniques promotes a more holistic representation of modern problems.

2. Study Areas

2.1. Lake Karla Watershed (LKW), Greece

Agricultural production is a major driver of the economy of the Mediterranean regions, while their relatively dry climate stresses water availability [13]. Increased production, efficiency and profit objectives often lead to water resource overexploitation and mismanagement.

In Greece, the lack of rational irrigation water management is becoming more evident as water needs are hardly covered, especially in Thessaly, the country's driest basin district [14]. LKW in Thessaly is an intensively cultivated area of 117,300ha, with overexploited water resources (its aquifer, river Pinios, and Lake Karla) (Figure 1a). Losses from evaporation, leakage, inefficient irrigation practices, intensification of agriculture, illegal wells, lack of economic management, project planning and political will to address the conflicting agricultural and environmental sides, complete the frame with the major concerns [15,16]. The farmers often protest against potential environmental measures, while subsidies and product prices have been driving the policy making so far. The problem of optimal water resource allocation and use-efficiency in the region has been approached through simulation and management models [17], while a few studies applied optimization techniques for water management in Thessaly. These refer to agricultural production maximization techniques, optimal management of the overexploited aquifer of LKW, the cost-effectiveness of irrigation practices, and the irrigation water use efficiency considering physical and economic parameters [18–20]. In this work, the optimization example presented for LKW maximizes net profits under different environmental constraints, providing answers on the degree up to which the first negatively affects the latter. To our knowledge, this approach is here applied for the first time in this study area, namely with the aim to shed light on the trade-offs of profits versus environmental constraints, based on farmers' decisions on crop selection.

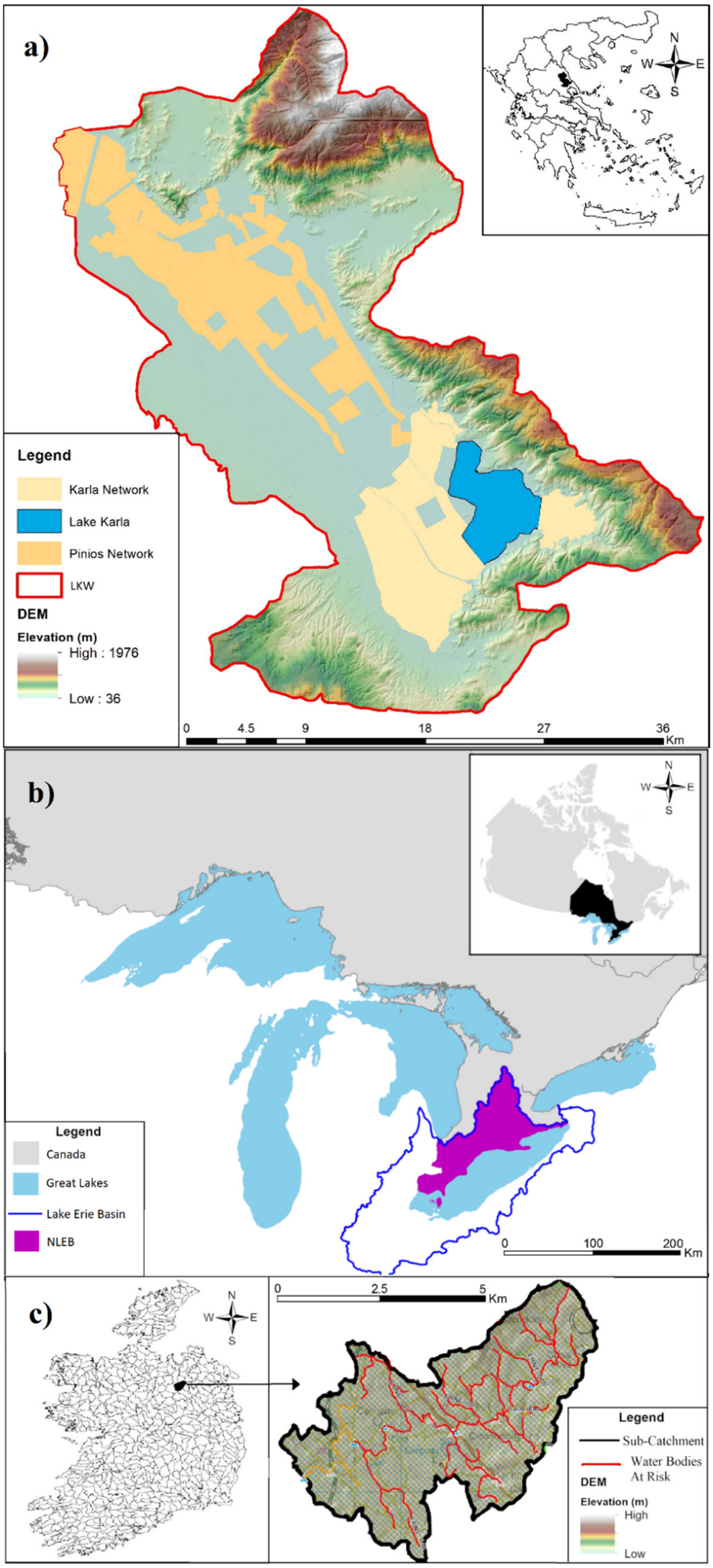

Figure 1. The three sites used for the modelling examples: (**a**) Lake Karla Watershed (LKW), (**b**) Norhten Lake Erie Basin (NLEB), (**c**) Erne Sub-Catchment Area (ESCA).

2.2. Northern Lake Erie Basin (NLEB), Ontario, Canada

Ontario's Action Plans consider several strategies to improve water quality, focusing on the reduction of phosphorous (P) runoff from agricultural to Lake Erie to tackle eutrophication [21]. Governmental goals for controlling nutrients' concentrations have been set, and the reduction of P runoff up to 40% is the major one [22,23].

The main research focus so far has been on pollution control, rather than the trade-offs between environmental (water quality) and economic (agricultural production) objectives [24–27]. Subsequently, the research question arising is how to balance the economic–environmental conflicts—how to achieve same or higher profits with reduced nutrient exports [28]. The literature highlights the need to combine all affecting factors into a single model to guide informed decisions. On this basis, this work provides an optimization framework to address the trade-offs of agro-economics, subject to environmental (pollution) constraints, at the NLEB, which includes 274 watersheds and sub-watersheds (2,270,000 ha) directly running off to Lake Erie (Figure 1b). Optimization has been used so far for other purposes in rural Canadian studies, such as maximizing cropping yields and production or minimizing production costs [29,30]. To our knowledge, this is the first application of farmers' profit maximization through the optimum crop distribution under pollution control constraints. Similar to the logic of the first case (LKW), the focus is to inform about the trade-offs between economics and pollution reduction conditions, depending on farmers' decisions on the cultivated crops. The model considers a range of continuous values, instead of upper and lower limits, as assumed by the existing measures so far.

2.3. Erne Sub-Catchment Area (ESCA), Ireland

Ireland is a primarily rural country, where animal farming is a significant economic driver. Agriculture is the main cause of diffuse pollution (fertilizers, pesticides with low nutrient-use efficiency, manure and Carbon (C) emissions) [31]. Agriculture accounts for approximately 30% of Ireland's GHGs emissions [32], the negative impacts of cattle access to water bodies on their quality have been extensively highlighted [33], and all the above fundamentally disrupt P and N cycles and deteriorate water quality [34].

The rural layout of the country includes many small local communities and only a few urban centres. The water management is carried out by privately (locally) voluntary owned and operated schemes, or the Group Water Schemes (GWS), which support the construction, operation and maintenance of water supply and distribution systems from local sources such as lakes or boreholes into homes and farms [35]. The National Federation of Group Water Schemes is the representative organisation for the community-owned group water scheme sector in Ireland [36]. Although the Environmental Protection Agency (EPA) and the Local Authorities provide general guidelines and programmes on pollution control (better management fertilizers, manure, etc.), the monitoring and management of pressures and measures' impact on informing relevant decisions in practice is still in poor.

ESCA (Figure 1c) covers 9840 ha and was chosen as a typical case facing agriculture's diffuse pollution with excess nutrient losses and GHG emissions, like most Irish catchments [37,38]. The main information source for most areas is the River Basin Management Plans (RBMPs), a requirement of the European Water Framework Directive, where every Member State must outline measures to restore and protect the status (quantity and quality) of the water bodies, operating over 6-year cycles. A basic monitoring–characterization process is in place, using high–moderate–poor–at risk status categories, as per the Water Framework Directive. All ESCA's surface water bodies are historically of poor quality [39], were characterised as 'poor status' (2010–2015), having further deteriorated since the 2007-09's assessment [37]. The recent assessment for the 3rd Cycle of the RBMPs showed no improvement in the sub-catchment's water bodies [38]—where all the surface water bodies were characterised "at risk" (meaning that it is unlikely to achieve good ecological status by 2027). Two lakes (Kill and Graddum) and the groundwater are the drinking water sources for the catchment. The two lakes are "not on a published monitoring programme", their status is "unassigned" since 2007, while the groundwater is "under review"; and both river bodies are at risk and without any chemical monitoring [40]. The responsible Local Authority (LA) is Cavan County Council and the main measure suggested by the RBMP refers to its planned work 'and potential to build on findings'.

Agricultural practices, the food and livestock industry development, and the pollution from agriculture is being studied and modelled by Teagasc (Agriculture and Food Development Authority), and certain Irish research centres [41]. Very few integrated approaches have been proposed so far, focusing in a smaller and very detailed scale e.g., Breen et al. [42] and their work on dairy farms. There has been limited focus on finding ways to address the conflicting issues of the agriculture's expansion and the environmental degradation at a larger (catchment) scale. This work presents a Goal Programming model, considering various environmental, economic, agronomic, and social objectives to explore their trade-offs, for the first time for ESCA and Irish agriculture.

3. Methodology

3.1. Linear, Non-Linear and Goal Programming

An optimization process using linear programming assumes a linear objective function (Z) set as a goal for maximization (or minimization) of, under linear constraints, all functions of the decision variables (Equation (1)):

$$Z_{\text{max (or min)}} = f\ (x_1, x_2, x_3, \ldots, x_n) \tag{1}$$

where ($x_1, x_2, x_3, \ldots, x_n$) are the decision variables, the system's data. In addition, the process must satisfy a set of constraints, the acceptttttttttt range of values of which are (Equation (2)):

$$u_i\ (x_1, x_2, x_3, \ldots, x_n) \le a_i \tag{2}$$

where a_i: known values. The optimum solution of the system must meet all the constraints and the objective function.

This practically provides a useful set-up for problems like the ones described in the previous section, because an objective (goal) can be maximized or minimized while exploiting the optimum levels of the other parameters of the system (controlled as constraints), all depending on the decision variables.

In the case of non-linear programming, the relations of Equations (1) or (2) are described by non-linear functions. These problems are in general harder to solve; however, optimality can be guaranteed when certain conditions are met by the problem.

Goal Programming is a powerful and flexible technique that can be applied to a variety of decision problems involving multiple objectives [43]. It attempts to minimize the set of deviation from multiple pre-specified (desirable) goals which are considered simultaneously. The analyst or stakeholders can weight those goals according to their importance, in a way that, for example, penalizes the deviations from them (so that lower order goals are considered only after the higher order goals). The general Goal Programing model is based on a linear programing model (Equation (3)):

$$\text{Min Z} = \sum_{i=1}^{m} \sum_{k=1}^{K} P_k \left(w_{i,k}^{+} d_i^{+} + w_{i,k}^{-} d_i^{-} \right) \tag{3}$$

The goals are expressed by the 'm' component and P_k is the priority coefficient for the k-th priority. '$w_{i,k}$' represents the weights of each goal. The deviational variables d_i^{+}, d_i^{-} represent the amount of over-achievement and under-achievement of the i-th goal, respectively.

The constraints (Equation (4)) are expressed through the decision variable 'x_j' and the b_i and a_{ij} coefficients for the j-th decision variable in the i-th constraint.

$$\begin{aligned} &\sum_{j=1}^{n} a_{ij}x_j + d_i^- - d_i^+ = b_i \quad for\ i = 1,2,\dots,m \\ &\sum_{j=1}^{n} a_{ij}x_j \ (\leq = \geq)\ b_i \quad for\ i = m+1,\dots,m+p \\ &x_j, d_i^-, d_i^+ \geq 0 \quad for\ j=1,2,\dots n, \quad i=1,2,\dots,m \end{aligned} \tag{4}$$

where $w_{i,k}^+$ the weight for the d_i^+ variable in the k-th priority level and $w_{i,k}^-$ the weight for the d_i^- variable in the k-th priority level. Each deviation can be divided by the range between the best and the worst achievable value in order to attain all values between 0 and 1.

These approaches are not methodologically new, but were chosen due to their relatively simple structure, suitability to the studied problems' characteristics, their expression through relations that can be easily modified if needed, and their ability to provide straightforward and clear-cut solutions in a reasonable computational time and capacity. Moreover, one of the aims of this work is to show that even such standard techniques, if applied properly, can give answers that currently are unknown for these particular areas [44–46]. So, given their replicability, there can be important policy implications towards a more holistic and informed management. The software used for the development and solution of the problems was Python (Anaconda), which is free and reliable for linear programming, non-linear, integer and mixed-optimization problems [47].

Below there are three sections, one for each case study, describing the models used based on linear, non-linear, and goal programming. It should be clear that each case study could be approached by either technique, as all of them are capable of showing the trade-offs between the maximized profits under different environmental constraints. As the results show, all different models can provide useful insights, improving the site-specific current management practices.

3.2. The LKW Model

A linear optimization problem was developed to represent the case of LKW. The model maximizes the profits from the agricultural activities, subject to the watershed's area, water, fertilizer, and labour constraints (Table 1).

Table 1. Mathematical description of the LKW model (annual values).

Relation	Description
$x_i, \quad i = 1,..,18.$	Decision variable x_i represents the area allocated to each crop i in [ha].
$\max NP = \sum_i np_i \cdot x_i \quad (5)$	The objective function is the maximization of net profits in [€]. The coefficient np_i represents the net profit per area of each crop [€/ha].
$\sum_i x_i \leq \text{TotalArea} \quad (6)$	1st constraint: not to surpass the total available cultivated area [ha].
$\sum_i wr_i \cdot x_i \leq \text{TWA} \quad (7)$	2nd constraint: the water requirements for each crop (wr_i in [m³/ha]) not to exceed the total water availability (TWA), i.e., the renewable water resources [m³].
$\sum_i fert_i \cdot x_i \leq \text{TF} \quad (8)$	3rd constraint: not to surpass the current applied fertilization quantity from all crops' requirement in [kg].
$\sum_i lb_i \cdot x_i \leq \text{TL} \quad (9)$	4th constraint: not to exceed the total available labour hours for work on the cultivation of crop in [hr].
$x_i \geq x_i^{\min} \quad (10)$	5th constraint: sets a minimal bound of cultivated area for each crop.

Equation (10) ensures the optimal solutions do not abruptly diverge from the cultivation pattern observed during the last ten years in the area. This is ensured by setting a lower bound of cultivation area for each crop.

The NP of Table 1 was estimated using a straightforward relation of the gross margin minus the total production cost. The gross margin is the sum of total revenue (production multiplied with product prices) plus the subsidies, while the production cost (for one unit of product) is given as the sum of the costs of lubrication, herbicides, seed, two sprays, defoliants, harvesting cost, pumping costs, oil, labor, planting cost, mechanical operations, and agricultural deductions [9]. In the process, 11 irrigated and 7 dry crops were used as decision variables (xi) and their typical economic data, water, fertilizer and labour requirements were retrieved from official data sources (Supplementary Material—Table SA1). The TF and TL were estimated using the existing crop distribution by using standard per unit values (e.g., kg/ha, hours/ha, respectively). The TWA were estimated based on the concept of the renewable water resources, in order to avoid negative water balances (water deficits), and thus environmental degradation; namely, the renewable surface (surface water runoff) and groundwater resources (recharge) were considered as 'water availability' [14]. The water availability was estimated using the hydrological model UTHBAL [14] to calculate, among other variables, the surface runoff and the groundwater recharge, i.e., the renewable surface water and groundwater resources [11]. This constraint is essential for this water-scarce area, as it allows the sustainable use of water resources, i.e., the renewable volume, rather than a practice of overexploiting the aquifer's stocks.

The scenarios tested on this model explored the different crop allocations that can be obtained from reducing the current water use in the basin. This was performed by reducing the baseline total water use by between 2% and 80%—an indicative wide range to cover a continuous range of all possible scenarios between those values. Therefore, the model provides a crop mix that is less water-intensive but still economically appealing to farmers by maximizing their net profit.

3.3. The NLEB Model

A linear model was initially used to express the objective and the constraints, according to the farmers' perspective, which is the maximum profit. The model finds the optimal area for each crop (decision variables) per sub-watershed, such that the emission reduction targets for P or N are met, according to the regulations of the fertilizer application, while ensuring that the current levels of water use and available area for cultivation are not exceeded (Table 2).

Table 2. Mathematical description of the NLEB model (annual values): 1st Version.

Relation	Description
$x_c, \quad c = 1,..,27.$	Decision variables X_c represent the area of each crop c in [ha].
$\max NP = \sum_{d\in D}\sum_c \left(pr_c\, y_c - prod_{cost\,c}\right) x_{d,c}$ (11)	Objective function of net profit (NP) maximization [CAD], as a function of each crop's product prices (pr_c in [CAD/kg]), average yield (y_c in [kg/ha]) and their typical production costs ($prod\_cost_c$ in [CAD/ha]). $x_{d,c}$ expresses the crops areas in [ha] as they are allocated per sub-watershed (d)
$\sum_c x_{d,c} \le TA_d, \ \forall d$ (12)	1st constraint: not to surpass the available cultivated area per sub-watershed (Total Area: TA) [ha]
$\sum_{d\in D}\sum_c wr_c\, x_{d,c} \le TWU$ (13)	2nd constraint: the sum of typical water requirement for each crop (wr_c in [m^3/ha]) not to exceed the total water amount currently used for irrigation (TWU) [m^3]. This constraint was applied for the whole range of TWU values from 0–50%, (each value representing a different scenario), to explore the irrigation water and profits trade-offs
$\sum_{d\in D}\sum_c fert_{j,c}\, x_{d,c} \le TF_{d,c,j}$, $\forall j$ (14)	3rd constraint: not to surpass the already implemented fertilization (TF_c) [kg] from each crop's requirement in fertilizers ($fert_c$) [kg/ha]. Three constraints were applied in this context, one for each of the following fertilizers, j = N, P_2O_5, K_2O

$\sum_{d\in D}\sum_c P_c\, x_{d,c} \le P_{des}$ (15)	4th constraint: reducing P exports to desirable levels (P_{des}) [kg] from each crop's P export coefficients (P_c) [kg/ha]. This constraint was applied by using scenarios for the whole range of reduction percentages of P_{des} (from 0–50%, according to the governmental goals [22,23])
$\sum_{d\in D}\sum_c N_c\, x_{d,c} \le N_{des}$ (16)	5th constraint: reducing N exports to desirable levels (N_{des}) [kg] from each crop's N export coefficients (N_c) [kg/ha]. This constraint was applied by using scenarios for the whole range of reduction percentages of N_{des} (from 0–50%, according to the governmental goals—[22,23])
$y_c = \sum_{d\in D} y_c\, x_{d,c}$ (17) $y_c^{min} \le y_c \le y_c^{max}, \quad \forall c$	The areas of the crops cannot change totally randomly, but in line with each sub-watersheds' production goals. Minimum and maximum y values were imposed to limit the impact of potential supply shocks to the market. A range of 50–150% of the current production was used, based on each crop's historically observed areas $x_{d,c}$, accounting for permanent crops and non-productive periods [24].

The examined policy suggests an optimization of the cropping distribution of the province's sub-watersheds, as mentioned in the study area section. Thus, the algorithm solves the problem 274 times. The analysis was carried out for the whole range of scenarios considering the reductions of TWU, Pdes, Ndes (and their combinations) in order to provide the trade-offs between these parameters (representing the different policy goals) and the NP.

2nd Version of NLEB model

This model was also tested considering that the optimized crops' areas will translate to a different supply to the market, affecting thus the product prices. These changes, driven by the optimized crop distributions, were studied in this 2nd version of this model. This modified version becomes non-linear, using the elasticity of the supply to the product prices, answering the problem of reaching the Pareto frontier of the optimal trade-off between production and the associated market's behaviour.

The elasticity of supply (ε), was a new constraint to account for the price change (Δprice) that is triggered by the changes in supply (Δy) compared to its baseline values ($\mathrm{price}_0, \mathrm{y}_0$ respectively), using the elasticity of supply (Equation (A.1)) [48,49]:

$$\frac{\Delta y}{\Delta price}\frac{price_0}{y_0} = \varepsilon \quad \Longrightarrow \quad \Delta price = \frac{1}{\varepsilon}\frac{\Delta y}{y_0} price_0 \tag{18}$$

The same objective function was used (Equation (11)), which becomes non-linear, since the product price (pr) is now variable, denoted by 'newPrice' (Equation (19)), and expressed by the additional constraint of Equation (20).

$$max\ z = \sum_{d\in D}\sum_{c\in C}\left(newPrice_c\, y_c - prod_{cost_c}\right) x_{d,c} \tag{19}$$

$$\begin{aligned} newPrice &= price_0 + \alpha\, \Delta price \\ &= price_0 + \alpha \frac{1}{\varepsilon}\frac{\Delta y}{y_0} price_0 \\ &= price_0 \left[1 + \frac{\alpha}{\varepsilon}\left(\frac{y}{y_0} - 1\right)\right] \end{aligned} \tag{20}$$

$\alpha \in [0,1]$ is a factor to account for supply dominance of the region and the degree of its influence over the price, and $\varepsilon < 0$ is the elasticity of supply. These parameters are defined by the analyst based on how each supplier affects the market prices. In this example, α was conservatively set 0.2 and ε to -0.2 following [24,48,49]. All data were retrieved from official sources and are listed in further detail in the Supplementary Material (Table SA2).

The modified version can be applied for both LKW and NLEB cases, and it is the main methodologically novel element compared to the existing optimization approaches.

3.4. The ESCA Model

A goal programming (GP) model was developed to depict the situation of ESCA in a representative way for Irish agriculture and its animal farming concerns in general. The objectives set maximum sales, minimum production or capital costs, maximum exploitation of available area, minimum emissions of Phosphorus and Carbon, maximum organic fertilizer and minimum use of chemical fertilizer, maximum expected production, and minimum water use. The model allows for deviations (d) from one or more expected (or desirable) targets, and the policymakers can penalize those deviations as exceedances (+) or deficits (-) by weighting them (w: degree of undesirability of deviations). The model minimizes these deviations from the desirable goals, and also provides the optimal values of different animal types (decision variables), as well as for each goal set (Table 3). Three decision variables were considered, accounting for the main farming activities in Ireland: beef, dairy, poultry. The above (variables, goals and constraints) are indicative, as the user can easily omit goals and decision variables, or add more (e.g., crop types, or more animal types, minimize labour hours, maximum use of machinery, minimum transports, minimum N, etc.).

Table 3. Mathematical description of the ESCA model (annual values).

Relation	Description
$\mathrm{X} = beef, dairy, poultry$	The decision variables: beef cows (beef: with index 1 in [heads]), dairy cows (dairy: with index 2 in [heads]) and poultry hens (poultry: with index 3 in [heads])
$\text{Min Z} = \sum_{i=1}^{m} \sum_{k=1}^{K} \left(w_{i,k}^{+} d_i^{+} + w_{i,k}^{-} d_i^{-} \right)$ (21)	The objective function minimizing the deviations (d) of the desirable goals (i), weighted depending on their importance (w)
$s_1 \cdot \text{beef} + d_{s1}^{-} \geq \text{TypicalSale}_1$ $s_2 \cdot \text{dairy} + d_{s2}^{-} \geq \text{TypicalSale}_2$ $s_3 \cdot \text{poultry} + d_{s3}^{-} \geq \text{TypicalSale}_3$ (22)	Goal 1: Maximize the sales [€/year]. s_1, s_2, s_3 are the average earnings from livestock [€/head]. $\text{TypicalSale}_{1,2,3}$ are their respective Typical Sales [€]
$c_1 \cdot \text{beef} + c_2 \cdot \text{dairy} + c_3 \cdot \text{poultry} - d_c^{+} \leq$ Budget (23)	Goal 2: Minimize the total production or capital cost. c_1, c_2, c_3 are the production or capital costs for livestock [€/head]. 'Budget' stands for an indicative expense scheduled to cover any production and capital costs [€]

The model will provide the optimum herd size for poultry, beef and dairy cows, in order to achieve the minimum deviation from the environmental and economic targets set (quantifying them). More specifically, this approach can ensure the minimum deviation for expected sales, costs, organic fertilizer use, while the available water and area, chemical fertilizer, P and C emissions will not be exceeded. The data used were retrieved from official statistical databases, representative for the study area and Irish agriculture (see Table SA3 of Supplementary Material). The weights (w) for each goal's deviation were set by the analysts, as this is an indicative (demo) example; however, it is suggested defining them through workshops with the local stakeholders having direct and indirect interests to the problem's factors. Thus, it will be easier for them to understand the problem, its assumptions and trade-offs, making it easier to reach an agreed plan (social acceptance) for implementation.

4. Results

The methodologies described in the previous sections were developed and solved in Python. This work aimed to demonstrate these optimization set-ups as approaches [1] for working with similar problems, so certain parameters defined by the analysts, can ideally be estimated through modelling (e.g., economic, hydrological, agronomic models).

4.1. LKW Model

Since the major concern of these regions is the availability of water for irrigation, the scenarios focus on decreasing water use without compromising profits for farmers. Initially, the model is solved for a zero water-use reduction to determine what would be the most profitable way to allocate the current water resources in irrigation. Then, a 20 and 40% reduction in water use is implemented. These reduction percentages are in line with previous research considering the demand management effect (e.g., conservation/water use efficiency after applying measures to reduce losses) [11,20].

The optimal results indicate that there are fewer water-consuming crop distributions that can maintain the current NPs for farmers. The optimal solution for the same water usage as the baseline shows that a more profitable crop selection can be achieved, increasing the profits by 11%. For a 20% water-use reduction, an alternative crop distribution can again achieve slightly higher profits for farmers. Finally, the scenario of reducing by 40% the water use shows that it is still possible to avoid sacrificing a large proportion of the profits, as in this case we have a decrease of only 15%. Figure 2 shows also the different areal magnitudes per crop, indicating that with a less conservative approach of crop distribution, even higher benefits could have been the results.

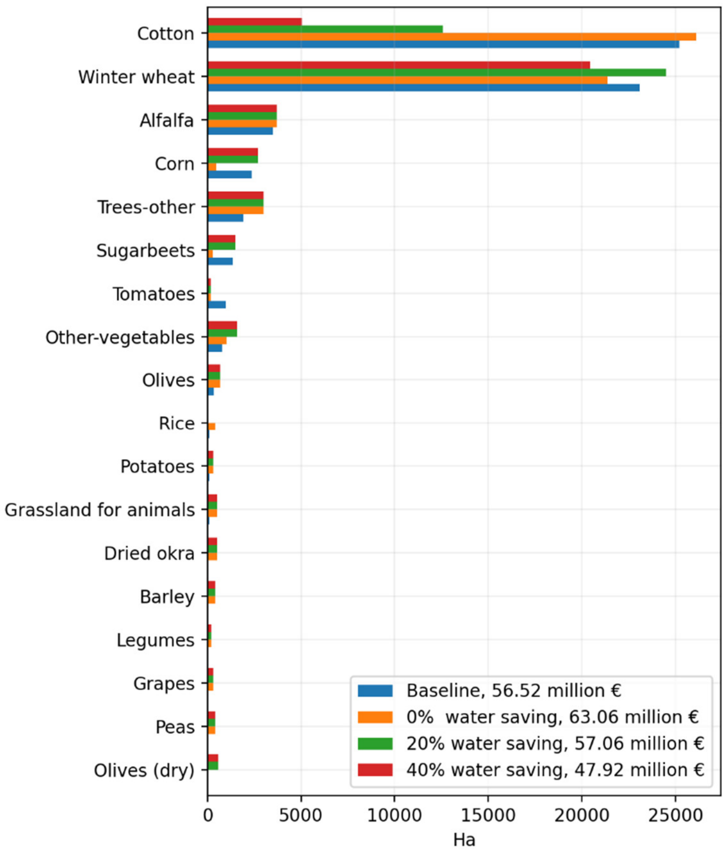

Figure 2. Crop areas for the baseline and the optimal solutions for water use reduction of 0, 20, 40%. The label shows the total annual profit for the crop selection.

In every scenario, the other constraints are reaching their threshold values, namely the same amount of labour hours, fertilizer and water use, while those in the baseline are maintained.

4.2. NLEB Model

The main concern of the NLEB case is water quality, not quantity. P and N exports from agricultural runoff were examined under the baseline and a range of scenarios, as mentioned. Table 4 shows the baseline values of the crops' production, P and N exports. As a first step, the optimization model was solved allowing the same total maximum nutrient exports, as in the baseline, to show the effect that an alternative (optimal) crop distribution can bring to production and thus profits. The results show there is a gain of 36%, by only changing the crop distribution.

Table 4. Crop production, P and N exports for the baseline and the optimum solution, allowing the same total maximum export of P and N as in the baseline.

Crops	Production [Tons/Year]		P Exports [Tons/Year]		N Exports [Tons/Year]	
	Baseline	Optimal	Baseline	Optimal	Baseline	Optimal
Total corn	9,981,214	6,674,986	3953	2644	8430	5637
Alfalfa and alfalfa mixtures	3,665,686	5,498,530	1112	1668	2973	4459
Soybeans	3,549,096	3,996,848	10,547	11,878	8864	9,982
Total dairy	2,364,101	1,403,045	1612	957	1269	753
All other tame hay and fodder crops	2,056,044	3,084,067	295	442	1576	2364
Tomatoes	530,059	795,088	57	85	48	72
Potatoes	408,591	612,886	39	58	66	99
Sugar beets	238,364	357,547	8	12	21	31
Oats	155,221	77,610	206	103	134	67
Barley	154,139	231,208	85	128	<1	<1
Apples total area	141,173	211,760	36	53	25	38
Mixed grains	111,150	55,575	183	91	312	156
Total rye	58,667	29,334	43	22	44	22
Other field crops	47,617	71,425	32	49	46	68
Dry white beans	44,019	66,029	21	31	70	105
Pumpkins	43,617	65,426	3	4	6	10
Cucumbers	36,015	54,023	5	8	5	7
Canola (rapeseed)	25,912	38,868	7	10	25	38
Cabbage	23,055	34,583	2	4	2	3
Ginseng	9729	14,594	9	14	16	24
Greenhouse vegetables	7096	10,645	2	2	2	2
Forage seed for seed	5273	7909	<1	<1	<1	1
Dry field peas	3407	1704	12	6	12	6
Other greenhouse products	1242	1862	<1	<1	<1	<1
Flaxseed	117	176	<1	<1	<1	<1
Mustard seed	116	174	<1	<1	<1	<1
Sunflowers	65	32	<1	<1	<1	<1

This finding is further demonstrated in Figure 3 for all scenarios explored, namely the whole set of values' combinations for P and N exports reduction, both ranging from 0–50%. Figure 3 shows how the profits are changing (Δutility) compared to the baseline value (zero-point) under all different levels of P and N reduction percentages. Taking into account all these combinations, the model produced a total of 676 runs. The results show that P exports can be reduced up to 42% and N exports can be reduced up to 46% while the profits from agriculture can remain stable or become higher, just be alternating the crop distribution.

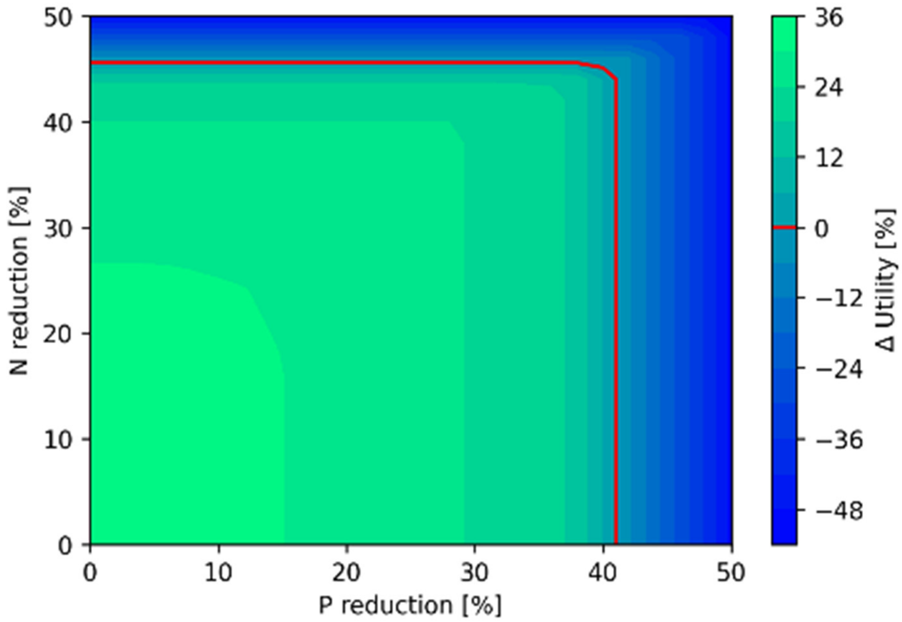

Figure 3. Change of profits in agriculture (Δutility) from the baseline for varying P or N reductions using the model's version 1. The red line shows the contour where the utility is the same as in the baseline.

The constraints were again maintained at the same levels, as in the baseline situation, while the effect of the optimized results of each scenario can be further explored for each crop. Commenting on the agricultural production of the region with reduced P and N exports, it was found that the same or higher production can be achieved. Indicatively with respect to the main crops, corn's production could be increased up to 20–30% for P and N exports reduction, 20–40% for dairy, alfalfa, tomatoes and potatoes even more than 40%, and soybeans up to 5–10%. It is worthy of mention that these values in reality can be further improved by applying BMPs, or other practices supporting farming and efficiency and pollution minimization.

<u>2nd Version of NLEB model</u>

This version was solved following decrements of P and N emissions by 10% (not the whole range of values as in Version 1). This was because this model is more computationally demanding than Version 1 due to its nonlinear constraints. Having a variable price as a function of the supply levels gives solutions where the utility is not increased. Thus, the optimal solutions do not offer a gain in profits in Version 1 (Figure 4). However, the Utility can remain at the same levels while the constraint values can be reduced. For example, with a 10% decrease in P and N, the Utility can remain the same, while it is slightly lower with a 20% decrease in P and N emissions.

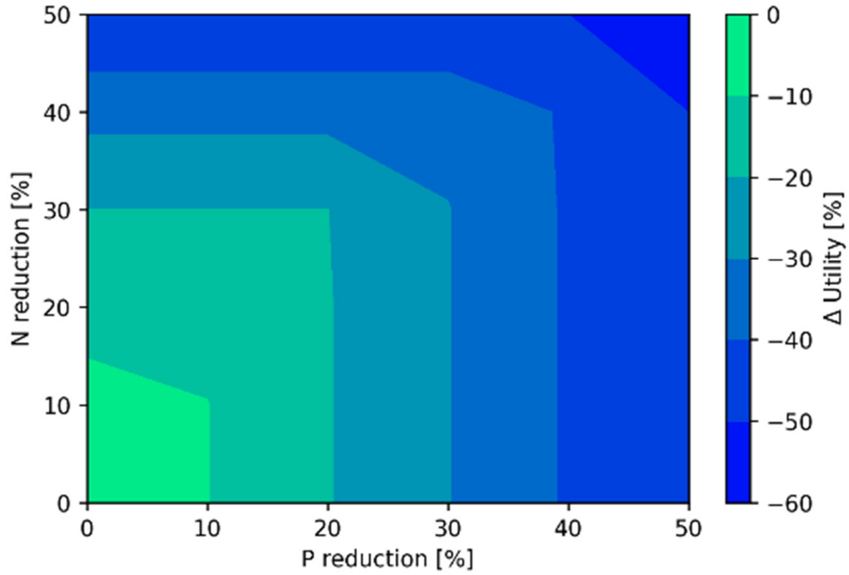

Figure 4. Change of annual utility with respect to the baseline for varying P or N reductions using the 2nd version of the model.

This version gives different (additional) answers to the problem, depending on the price changes relevant to the crop supply changes and P and N emissions, in order to avoid over- or under-production phenomena (inefficient market). It also provides the changes of the total production of the main crops as nutrient exports decrease. The production gradually decreases compared to the baseline production. For example, for a P runoff reduction of 40%, the dairy production decreases up to 50% and the corn production up to 20%.

Of course, these observations reflect the baseline situation change if no other measures are applied to improve the agricultural productive performance. Production, economic, and agronomic performances could be further improved by Best Management Practices (BMPs).

Overall, the 2nd Version's results suggest a more flexible cropping plan that will avoid overproduction, and lead to more efficient markets.

4.3. ESCA Model

Three scenarios were created following different preferences on the importance of achieving the economical or environmental targets of the model. These preferences are reflected by the penalization given to the deviations from the target values, i.e., each scenario differs only in the w_i's assigned to each goal (Table 5). The scenarios created are the following:

- Scen. A: Extremely environmentalist (only caring to have zero emissions and ignoring the other goals).
- Scen. B: Intensive farmer (only caring about maximum sales and profits, and then reduced costs while ignoring all the rest).
- Scen. C: A balanced penalization, representing the 'middle solution' between the first two scenarios.

Table 5. Weights assigned per scenario (scale 0–1).

Deviations Penalized	Scen. A	Scen. B	Scen. C
Deficit of beef sales (d_{s1}^{-})	0.0	1.0	0.5
Deficit of dairy sales (d_{s2}^{-})	0.0	1.0	0.5
Deficit of poultry sales (d_{s3}^{-})	0.0	1.0	0.5
Exceedance of costs—budget (d_{c}^{+})	0.0	0.1	0.0
Exceedance of P emissions (d_{e}^{+})	1.0	0.0	0.5
Exceedance of C emissions (d_{ghg}^{+})	1.0	0.0	0.5
Exceedance of organic fertiliser (d_{of}^{+})	1.0	0.0	0.5
Deficit of organic fertiliser (d_{of}^{-})	0.0	0.0	0.0
Exceedance of beef production (d_{y1}^{+})	0.01	0.0	0.005
Deficit of beef production (d_{y1}^{-})	0.01	0.0	0.005
Exceedance of dairy production (d_{y2}^{+})	0.01	0.0	0.005
Deficit of dairy production (d_{y2}^{-})	0.01	0.0	0.005
Exceedance of poultry production (d_{y3}^{+})	0.01	0.0	0.005
Deficit of poultry production (d_{y3}^{-})	0.01	0.0	0.005
Water deficits (d_{water}^{+})	0.05	0.0	0.05

A cultivated area of 4000 ha was assumed, with a 'budget' constraint of 150,000€/year, and 0.2 hm^3 annual water availability. The typical P and C emission targets are defined by European or national (local) policies as thresholds. In this example, these were set to 3350 kg/year and 45,000 kg/year respectively.

Scenario A (Scen. A) sets the criterion of controlling emission and pollution, so it prefers poultry farms, followed by beef and dairy cows. There are some losses in the sales of poultry, beef and dairy products, compared to the expected targets (e.g., current averages). The P and C emissions above the target (exceedances) are zero, as well as the water deficit and the organic fertiliser.

Scenario B (Scen. B), on the contrary, having primarily economic motives, prefers beef and dairy cows, and choses to surpass the budget constraint (by setting lower w_i) in order to over-produce and exceed supply and sales, aiming at higher profits. However, this results in significant water deficits and exceedance of P emissions.

Scenario C (Scen. C) as a balanced approach considers all three animal types: beef, poultry and then dairy cows. This achieves all the environmental objectives of Scen. A (P, C, water, organic fertiliser), with less losses of sales for beef compared to Scen. A, and also less losses of poultry sales compared to Scen. B. All the production targets are met, as well as the budget constraint, unlike Scen. B, and so economic objectives could be also satisfied.

Analyzing different factors in the same model is challenging; however, a more thorough picture of trade-offs can be seen under different scenarios representing different stakeholders. The results of Table 6 reflect the importance of planning multiple (conflicting) objectives together as a system in order to provide sustainable solutions. Such solutions are feasible, and the learnings from such models can support policymakers and practitioners to better understand complex systems. Similar approaches are encouraged in terms of building integrated databases that will lead to a holistic monitoring-modelling of the system as a whole, ensuring that no discipline will act at the expense of another.

Table 6. Results of the ESCA model per scenario.

Parameters	Scen. A	Scen. B	Scen. C
Beef (Heads)	71	200	130
Dairy (Heads)	48	181	48
Poultry (Heads)	107	-	107
Loss in beef sales (€/year)	16,099	-	8798
Loss in dairy sales (€/year)	19,941	-	19,941
Loss in poultry sales (€/year)	13,932	15,000	13,932
Exceedance of costs (€/year)	-	205,893	-
Exceedance in emissions of P (kg/year)	-	1002	-
Exceedance in emissions of C (kg/year)	-	-	-
Exceedance of Organic Fertilizer (kg/year)	-	8758	-
Deficit of Organic Fertilizer (kg/year)	7224	-	3895
Exceedance in beef supply (kg/year)	-	1,128,200	511,612
Deficit in beef supply (kg/year)	-	-	-
Exceedance in dairy supply (kg/year)	-	1,552,734	-
Deficit in dairy supply (kg/year)	-	-	-
Exceedance in poultry supply (kg/year)	-	-	-
Deficit in poultry supply (kg/year)	-	156,000	-
Water deficits (m^3/year)	-	2,358,911	-

5. Comparability, Limitations and Future Research

This research analyzed how the issues of resource shortage and pollution can be balanced (and to what degree) with agricultural objectives, in different contexts. The presentation of three different models aims to show that the main environmental pressure of each study area should be co-analyzed with all affecting parameters, especially the competitive dimension. The focus of these analyses (all three cases) is the exploration of the trade-offs among competing parameters. Of course, the three issues (water quantity, and pollution from cultivation and animal farming) might co-exist and can be modelled together, with additional functions expressing the policies of different countries, thus widening the solutions' space. The initial conditions (main pressures—conflict, trade-off of interest, water availability, quality, agricultural structure) are case-specific, and this is the main difference of the three models. Their common element is that they are new case-study applications, demonstrating how simple optimization set-ups could result in significant environmental and economic improvements compared to their existing situation. Building on such standard techniques, their replicability, as well as the insights provided (as this study shows), more informed decisions can be made. This, as an argument to trigger the necessary political will for more reasonable management, is also a novel element.

Unavoidably, any model that attempts to describe real situations cannot be perfect. An inherent limitation in such exercises is the data availability and quality. Trying to depict the situation in three rural areas, with the two smaller of them hardly being monitored, is ambitious. Precise input data in agriculture are difficult to collect, and this can affect the models' outputs. Among our cases, NLEB had the more complete and organized data, and this allowed us to develop two versions of this model, taking into account several crops and parameters. However, in all three cases most data used are obtained from official databases, all of them were validated with locals, the existing literature, and are based on average annual values, so as to have as representative and accurate models as possible. In the future, specific parameters can be defined considering the case- and market-based features of each study area, if the data capacity and transparency increases. Thus, more flexible tools can be developed, able to better cope with the temporary nature of most data use, that are constantly changing.

Another limitation is that no local stakeholder analysis was carried out to weight the goals and evaluate their importance, because the aim at this point was to describe the methods. However, this is absolutely required in future studies, and we have already started such efforts using the learnings and knowledge obtained from this work [44,50,51]. Stakeholders are keen on learning how multiple conflicting objectives can be modelled together and provide useful information [52,53]. Also, the proposed models are flexible, as users can modify the problems, add variables, constraints, etc. Through such engagement processes, additional measures for the more efficient resource management (BMPs) can be better targeted and implemented to further improve the systems' functions [54,55].

A final limitation that we identified is that instead of using typical average values for certain factors, ideally, we would like to base them on analytical models (e.g., water availability and use, fertilizer and nutrient exports, farmers and livestock economics). A two-way information process between hydrologic, agronomic, bio-economic models and the optimization models presented should be followed to complete the design implementation frame, and majorly expand the capabilities in planning. More specifically, time-series analyses, forecasts, examination of more physical scenarios (e.g., extremes, climate change, economic externalities, etc.) can be tested. Unfortunately, this could not be presented in the length of a single research paper, which already includes a lot of compressed information. However, we are planning to analyze one case-study more thoroughly in the near future.

In the present paper we have used three cases from developed countries, showing that the scientific input can significantly improve their current management practices in a more profitable and environmentally sustainable way. In case of considering study areas from developing countries, the environmental and socio-economic improvements would have been even more substantial [56,57], and apply to the broader context of the Water–Food–Energy Nexus [58,59]. The same and/or similar models can be used for case studies in developing countries, and the literature has been vast in such applications [60,61].

The expansion and coupling of the models presented in this study with environmental models in particular (e.g., Soil and Water Assessment Tool—SWAT, or GIS-based models, that use Python) is included in our future plans, and for that reason our three examples were developed in Python, in order to be easily compatible for future spatial optimizations. Of course, models provide useful answers, but not all the answers. The mindset of approaching several problems with conflicting objectives, in an integrated and inter-disciplinary way is the element highlighted most in this work. A conclusion is that even simple models and analyses can provide significant insights and, if applied right, can be highly informative; thus, any application is encouraged, especially in poorly managed sites.

6. Concluding Remarks

The main problem outlined in this study, through the three models examined, is the achievement of productive goals under environmental constraints. This reminds us of the definition of the economic problem, which in general tries to cover increasing needs with limited resources and controlled pollution (disturbance). Although there is no "one size fits all" plan for all case studies, a common approach used in all models presented can be beneficial: the analysis of the trade-offs among the competing factors can provide optimum sets of solutions (e.g., maximization of profits from agriculture, while water use and pollution are set to desirable thresholds). This approach (either as linear, non-linear, or multi-objective optimization) provided encouraging results for every case, in the form of alternative cropping plans or combinations of desirable goals. The results show that agricultural economies can be prosperous under environmental constraints, which can be tested under different conditions (scenarios, thus allowing the decision-makers to explore the trade-off of 'conflicting' parameters, understand how the system works, and finally agree on a plan. This social acceptance can be achieved by examining the different scenarios, as shown, and through the weights w_i for the ESCA case. Such processes can provide a basis for future collaborative planning between government and stakeholders, towards economically effective and environmentally sustainable management.

The parameters examined were chosen to depict the actual concerns of most policies, for example: the European Water Framework Directive, with its River Basin Management Plans, the Common Agricultural Policy, Nitrate Policies, Canada's Action Plans, Sustainable Development Goals, etc. [62]. All those plans have common goals to a degree, support sustainability, integrated management and multi-disciplinary approaches to balance similar issues [62,63]. This requires integrated databases and systemic understanding, which can be achieved through similar modelling processes. The nature of most modern complex problems is such that requires more scientific and data-driven approaches for their solution. Science and technology have provided theory, context, means and solutions for overcoming such problems. The implementation is up to the political will. Usually, policymakers are not likely to accept a new modelling approach, or even modelling itself, unless it is obvious that it will improve the performance of their work and help them address problems they are trying to solve [12]. From our experience in all three case-studies, stakeholders tend to seek more scientific approaches, to balance conflicts and achieve multiple benefits. Similar approaches will be highly valuable, especially during these times, where complex challenges occurred involving land management, agricultural water, energy and economic concerns. The war in Ukraine began during the end of this analysis, and the consequences will be particularly obvious in the LKW.

The transition to a multidisciplinary world with the modernization of traditional management practices requires respective knowledge and capacity, and this is increasingly highlighted by international (and national) policy agendas, and the complex challenges we face. These elements are optimistic for bringing knowledge out of the academic environment and collaborate towards a more sustainable future. Overall, systemic thinking and integrated analysis, stemming from optimization models, provides insights to policymakers or researchers about how to best tackle environmental or water usage problems in agriculture.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land11091548/s1, Table SA1: LKW model parameters; Table SA2: NLEB model parameters; Table SA3: ESCA model parameters.

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Note

[1] In every model the variables and constraints used can be modified to better tailor them for similar problems, depending the case and the data availability.

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