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Applications of DSSs in Irrigation and Production Planning in Agriculture

Jason Papathanasiou, University of Macedonia, Greece
Thomas Bournaris, Aristotle University of Thessaloniki, Greece
Georgios Tsaples, University of Macedonia, Greece
Panagiota Digkoglou, University of Macedonia, Greece
Basil D. Manos, Aristotle University of Thessaloniki, Greece

ABSTRACT

Agricultural management has become an increasingly complex endeavor. As a result, there is the need to generate knowledge from information that can guide practice, and in that aspect, decision support systems (DSSs) can contribute to achieving this goal. A DSS can be defined as a computer-based information system that is used to support complex decision-making. The aim of this paper is to present such a DSS focused on the agricultural sector. Its purpose is to be used for the planning of agricultural production and better utilization of a region's available resources. The development of the DSS relies on the classic theory of such tools utilizing MCDM models, databases, and a user interfaces. The proposed DSS was applied in the prefecture of Larissa in Central Greece. The DSS is adaptable to different contexts, and applications of these capabilities are presented at the end of the paper, applied in different regions under additional objectives and/or constraints.

KEYWORDS

Agricultural Production, DSS, Multicriteria Analysis, Sustainable Optimization

1. INTRODUCTION

Agricultural management has become an increasingly complex endeavor, since it must integrate typical production factors with an increasing need for sustainable use of the biological, physical and social capital, while trying to mitigate effects of climate change (Walker, 2002). This increased complexity has been recognized and been integrated in the goals of the European Union's rural policies, which are aimed at the socio-economic development of rural areas and the protection of the environment, through a sustainable management of agricultural production. Consequently, farmers are expected to address a wider range of issues (and their consequences) when making a decision.

As a result, there is the need to generate knowledge from information that can guide practice (Oquist, 1978). Furthermore, this information should be integrated under different criteria (Dutta et al., 2014) in order to produce multi-dimensional knowledge and actionable recommendations (Arnold, 2013; Nino-Ruiz et al., 2013).

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In that aspect, Decision Support Systems (DSS) can contribute to these goals. A DSS can be defined as a computer-based information system that can be used to support complex decision-making (Shim et al., 2002). They normally integrate databases and mathematical models to support the decision maker (Adelman, 1991) and in general should have the following attributes:

- They should reflect the process of thinking and decision-making of the decision-maker.
- They should be interactive.
- They should act as complementary tools to other decision-making techniques and processes (Turban, 1993).

As a result, DSSs were first applied in an industrial context (Bennett, 1983; Cox, 1996), where they were regarded as a mean to understand complex processes and were used to structure a problem and apply a mathematical algorithm to solve it.

They were grouped into two categories:

- Operational: Focused on everyday decisions that may be repetitive.
- Strategic: Focused on long-term decisions and planning actions that may involve group decision-making and/or negotiations (Walker, 2002).

Irrespective of their purpose, DSSs in agriculture are necessary because agricultural management has become increasingly complex and demanding in terms of time and expertise. Their advantages are that they can summarize information allowing a more holistic view and they can mimic an expert that constantly assists the decision maker (Plant & Stone, 1991). In conclusion, agricultural DSSs are necessary in order to survive economic and environmental crises (Mackrell et al., 2009), while ensuring sufficient production with less land, less labor and less water (De la Rosa et al., 2004).

The importance of DSSs in the agricultural sector has seen a surge of new applications. However, several key issues still need to be addressed:

- Real case studies could greatly increase the relevance and value of the research efforts on agricultural DSSs.
- More social factors need to be incorporated in the underlying mathematical models, shifting the focus from a purely technical to socio-economic (Arnold, 2013; Arnott & Pervan, 2016).

The purpose of the current paper is to present an agricultural DSS and contribute to the case study literature. The rest of the paper is organized as follows: On section 2, an indicative review of the literature is presented, while the main components of the DSS are described on section 3. Indicative results and scenario analysis are illustrated on section 4. Since the authors support the notion that DSSs should be updated and applied in real-life situations, section 5 is focused on such adaptations of the DSS to other regions and/or productions. Finally, conclusions are described on section 6.

2. LITERATURE REVIEW

The development of specialized DSSs has been accompanied by a growing interest from analysts and experts in the field of agriculture. While the general goal has always been to assist in the decision-making process in the field of agriculture, the goal can be customized and be operationalized depending on the individual circumstances. Hence, the aim of an agricultural DSS can be summarized in finding the best choice for cultivation, in exploiting to the maximum the available resources and in optimizing every aspect of the agriculture production.

As DSS models evolve, related publications on their agricultural applications also evolve. There have been various publications in the field in recent years. A relevant search has been performed in scientific databases with the terms "Decision Support Systems", "agriculture" and "decision making", with different combinations of derivatives and synonyms. At this point, it should be noted that the focus of the bibliographic search has been on Decision Support Systems and not on applying methods from Multi-Criteria Decision Making (MCDM) and/or Operational Research on the field of agriculture. It is our belief that this distinction is crucial since a DSS is a specialized piece of software that can be re-applied under different conditions and its development requires more than the application of such a mathematical/algorithmic method.

Consequently, the search revealed that from the latest 21 publications regarding decision-making in agriculture, 9 involved the development of a purely agricultural DSS. In the following paragraphs, these DSSs are analyzed.

The first DSS is named STICS and it is used to simulate the growth of crops by taking into account both environmental (such as water and nitrogen losses) and agricultural variables (yield and input consumption). Apart from providing indications on the rate of growth, the system assists in showing the consequence by calculating the nitrogen and soil water balances (Brisson et al., 2003).

Another similar system is the CropSyst. It attempts to offer a set of tools to analyze the environmental impact along with the field's productivity and the management of crops at various spatial and temporal scales (Stockle et al., 2003). APSIM consists of a group of modules that simulate the various stages of development/grow of crops, forests, and pastures, expressing their interactions with every type of soil. The difference with the previous systems is that through APSIM many different applications have been developed with its modules at their core. For example, it has been integrated in a system that assists farms to evaluate designs for their production in (Keating et al., 2003).

Another system that is focused not only on the production itself but also on its consequences on the immediate environment is EPIC. It provides information regarding decisions on irrigation, while taking into account erosion (water and wind), drainage, water efficiency, fertilizer, atmospheric conditions, and waste management solutions (Izaurralde et al., 2006). On the other hand, the DSSAT system is focused on crop variability. As a result, it is developed by combining independent modules, which operate together and provide the opportunity to incorporate models of sixteen crops, having important information about the evaluation of every crop (Jones et al., 2003).

A more recent approach has been proposed by Fenu and Malloci in (Fenu & Malloci, 2019), who developed a DSS for monitoring the main crop productions in Sardinia. The system is used to collect, organize, integrate and analyze many types of data with several mathematical models, while it is used to forecast the risk of late blight in potatoes in Sardinia. Furthermore, (Rupnik et al., 2019) took advantage of the latest cloud technologies to develop a cloud-based DSS named AgroDSS, which also includes data mining tools for processing and analysis.

On the other hand, (Gardas et al., 2019) consider agricultural management as part of a wider supply chain management issue and use the Delphi method, DEMATEL and interpretive structural modeling to identify and analyze challenges in India. Finally, the wider issue of climate change could not remain separated from agriculture. (Rowshon et al., 2019) and (Han et al., 2019) developed climate-aware decision support systems for agricultural decision-making.

Apart from the DSSs that are focused mainly on agricultural productions, there are also others that investigate different aspects of agriculture. (Seyyedhasani et al., 2019) developed a system to calculate the routing efficiency of vehicles that work on fields. The authors used two routing algorithms, a tabu search meta-heuristic, and a Clark_Wright heuristic, using 100 different field shapes tested under 1200 different scenarios, calculating each time the efficiency of every route. Another interesting approach is a model of agricultural technologies, which is based on intuitionistic fuzzy sets by (Ciric et al., 2019). In order to focus on the best financial effects, the authors created a model that calculates whether or not the land is arable, taking into consideration the biological and the technological conditions, the economic environment, and the expertise and workmanship quality, while linguistic values of those are used with intuitionistic fuzzy sets. (Arbolino et al., 2018) have used a methodology for solid biomass planning in several areas, using a combined optimization approach. The authors try to find the best investment solution in marginal areas with a multi-objective optimization model, while they use benefit-cost analysis to explore the feasibility of every agricultural investment, with a pilot testing application in Italy and Germany in order to test their approach.

The authors of the present paper make no claim that the above list is exhaustive; the field of agricultural decision-making is vast and varied. For example, (Sumpsi et al., 1993; Sumpsi et al., 1997) and (Amador et al., 1998) were among the first to illustrate how the use of mathematical programming techniques could assist in analyzing how Common Agricultural Policy rules could affect the production. However, the chosen works that were described above indicate the variability that characterizes the field in the last years.

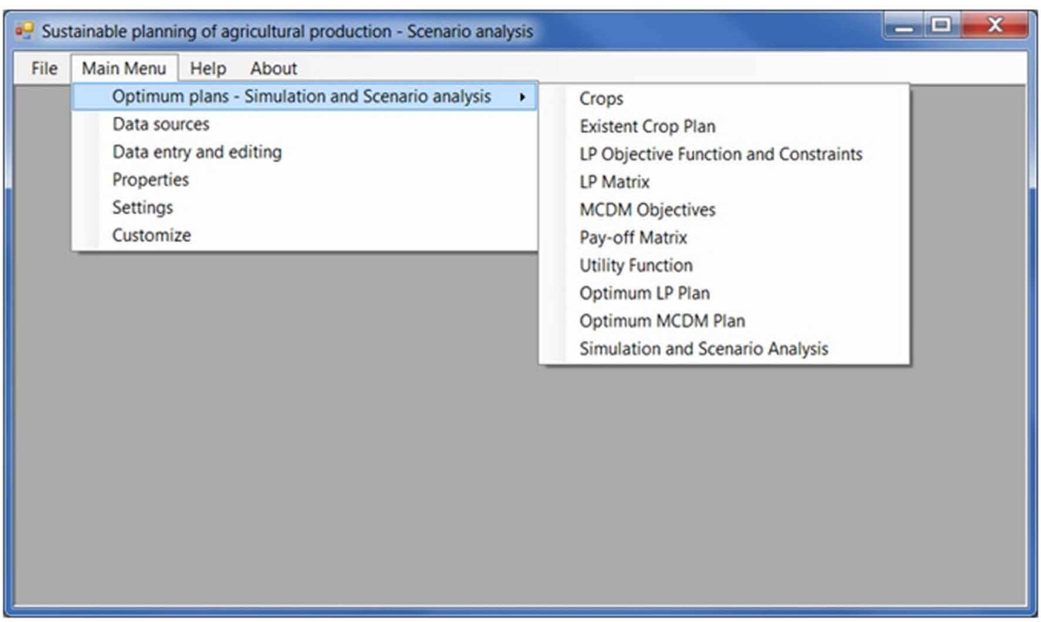
3. METHODOLOGY

Despite the different approaches and uses of the various DSSs, there are commonalities especially regarding how they are developed. A typical DSS is composed of (fig. 1):

- The Database (DB) and the Data Base Management System (DBMS).
- The Model Base (MB) and the Model Base Management System (MBMS).
- The User's Support Management System (USMS).

The purpose of a well-organized database is to facilitate the correct and systematic data entry, storage and management, while the models base contains the mathematical models to process the data that will assist in the decision-making process. Furthermore, the models' base can be used for sensitivity analysis and analysis of different scenarios. Finally, a successful DSS is wrapped in a user-friendly interface that allows its use from non-experts.

Figure 1. The main components of a DSS



The purpose of the present DSS is to be used for the optimization of the available production resources of a region, implying the increase of the region's average income, while reducing the labor needs, the use of nitrate fertilizers and the use of irrigation water.

For its development, the programming language of Visual Basic .NET was used; the database was developed on Microsoft Access and the mathematical programming tools with the help of the specialized software of LINDO and LINGO. The following paragraphs provide details on the individual modules of the DSS.

3.1. The Database (DB)

The database (DB) is used to import and store the technical and economic data of the selected crops (prices, yields, etc.) and the available production factors (various types of land, capital and labor) of the agricultural region, i.e. the DB contains all the necessary technical and economic information, which is being collected from primary and secondary data sources.

The necessary data were collected by:

- A sample of farms of the region under study.
- The Directorate of Agriculture in Larissa prefecture.
- The region of Thessaly.
- The Hellenic Statistical Service.
- Eurostat.
- The Department of Agricultural Economics of the Aristotle University of Thessaloniki.

3.2. The Model Base (MB)

The Models Base uses the appropriate data from the Data Base, analyzes them with the available models and extracts the final results. It includes a Linear Programming (LP) and a Multi Criteria Decision Making (MCDM) model that are used for the optimization either of a single objective or the simultaneous optimization of multiple conflicting objectives that are combined in one common utility function, subjected to a set of constraints, such as the available production resources, the market, the Common Agricultural Policy rules (CAP), etc.

The MCDM model weighs the multiple conflicting objectives with the use of Weighted Goal Programming. The use of Weighted Goal Programming is extensive in the agricultural field. For example, it has been used to assist in water agricultural policy (Berbel, 1993; Manos et al., 2009; Rizov, 2004) and in farm planning (Gomez-Limon & Atance, 2004; Hardaker et al., 1991). The purpose of the LP and MCDM models is the optimization of the available resources in the agricultural production (various types of land, labor and capital).

In more detail, the DSS optimizes the following objectives:

- Maximization of the gross margin.
- Minimization of the labor use.
- Minimization of the use of nitrate fertilizers.

The LP model optimizes one of the objectives at a time. The MCDM model, by using the Weighted Goal Programming, estimates the weights of each objective/criterion. It then integrates all objectives/criteria into a common utility function that is used as the objective function of the MCDM model. Both the LP and MCDM models are subjected to the same set of constraints: total cultivated area, CAP constraints (production rights, quotas and fallowing), limitations concerning the market and constraints in crops rotation and irrigation. Both models calculate the required quantity of irrigation water, in parallel with the value of the objective function.

3.3. The User's Support Management System (USMS)

The USMS entails all the necessary interfaces, menus and sub-menus that will help decision-makers and end-users to better use the DSS. There are 10 steps in the main menu and the end-user or decision maker must complete each step before moving to the next one (Figure 2).

3.4. Use Case of The DSS

As it was mentioned above, the purpose of the DSS is to find the optimal production plan given the available production resources of a region, while taking into account sustainability issues such as labor needs, use of nitrate fertilizers and use of irrigation water.

More specifically, the LP model provides three alternative production plans each of which achieves either the maximum gross margin or minimum labor use or minimum fertilizers' use. For each production plan, the combination of the crops along with the total gross margin and the total labor use is provided. Moreover, the DSS calculates for each proposed plan, the required volume of irrigation water and nitrate fertilizers, both of which are important environmental factors. Finally, the three proposed production plans are compared to the existing production plan, not only on the crops, but also on the achieved technical and economic results, thus providing useful information to policy makers of the region.

The results are presented by the DSS in the form of tables and graphs that compare the proposed plans with the existing one. The DSS has been applied in the prefecture of Larissa in Central Greece. An extensive presentation and discussion of the results can be found in (Manos et al., 2017; Manos et al., 2015).

4. RESULTS

The proposed DSS was applied in the prefecture of Larissa in Central Greece, where it was used to indicate the optimum production plan. The area is one of the most extensive agricultural plains in Greece, with main crops including wheat, cotton and maize (Region of Thessaly, 2007). Nonetheless, the area is characterized by high degree of fields' fragmentation, underemployment of the labor force and increased prices of land. Thus, agricultural activity is costly.

Figure 2. Main menu of the DSS

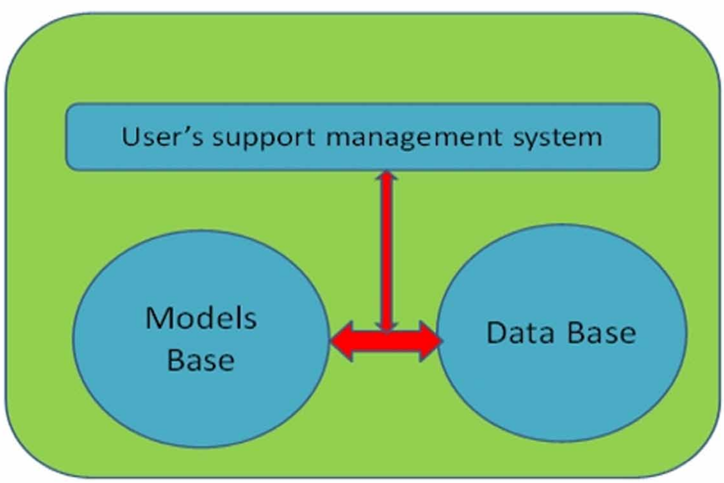


Figure 3 below illustrates the results obtained by the DSS, when comparing the optimum plan with the existing one. The results illustrate the type of crop used and the percentage it covers in real life, while the optimum plan illustrates the proposed coverage when the objective is optimized.

For example, under the existing plan, maize is cultivated at a percentage of 5.26% (fourth line of the table on the left), while the optimal plan -considering the various characteristics of the area and operational constraints – indicates that it covers a larger part of the production plan that it is efficient; according to the DSS maize should be cultivated at 0.73%, presenting a deviation of 86.12% to the real-life circumstances (third line of the table on the right).

Furthermore, the results are translated into economic terms (Figure 4). Column 1 indicates the Gross Margin, Fertilizer Use, Labour hours and Water Demand. The results from the use of the DSS show that the optimum plan resulting from the MCDM model increases the profit and decreases the rest of the terms, making the proposed plan more effective than the one already used. For example, should the proposed plan be followed, the fertilizer use (in Kg) could be decreased up to 5.39% of the current use, leading to substantial savings for the farmers and less pollution for the environment.

The DSS provides also graphical representations of the obtained results, which increases the ease of communication. For example, Figure 5 below translates the results obtained in Figure 4, into a bar chart that clearly shows the effect that it would have on the objectives, should the proposed plan have replaced the existing one.

Finally, the proposed DSS can be also used for the analysis and simulation of the production plans under different scenarios with different combinations of the socio-economic and environmental variables such as:

- Different prices of products and resources.
- Different level of utilization of the available resources (such as different categories of land, labor and capital).
- Different policies of CAP and Rural Development Program.

Figure 3. Comparison of crops between the existent and the optimum MCDM production plan

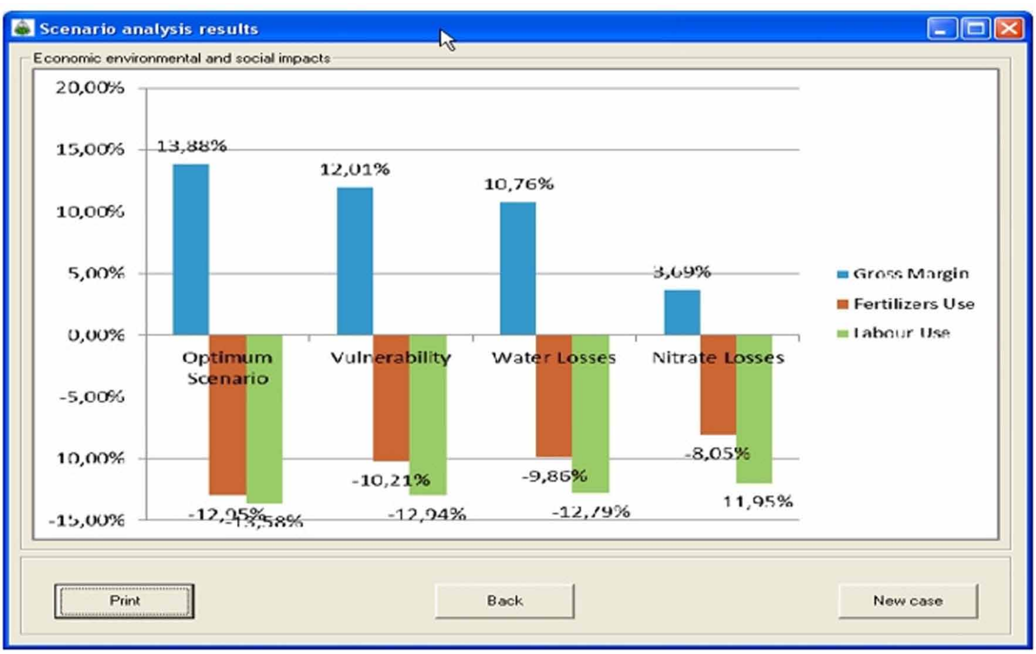


Figure 4. Comparison of economic results between the existent and the optimum MCDM production plan

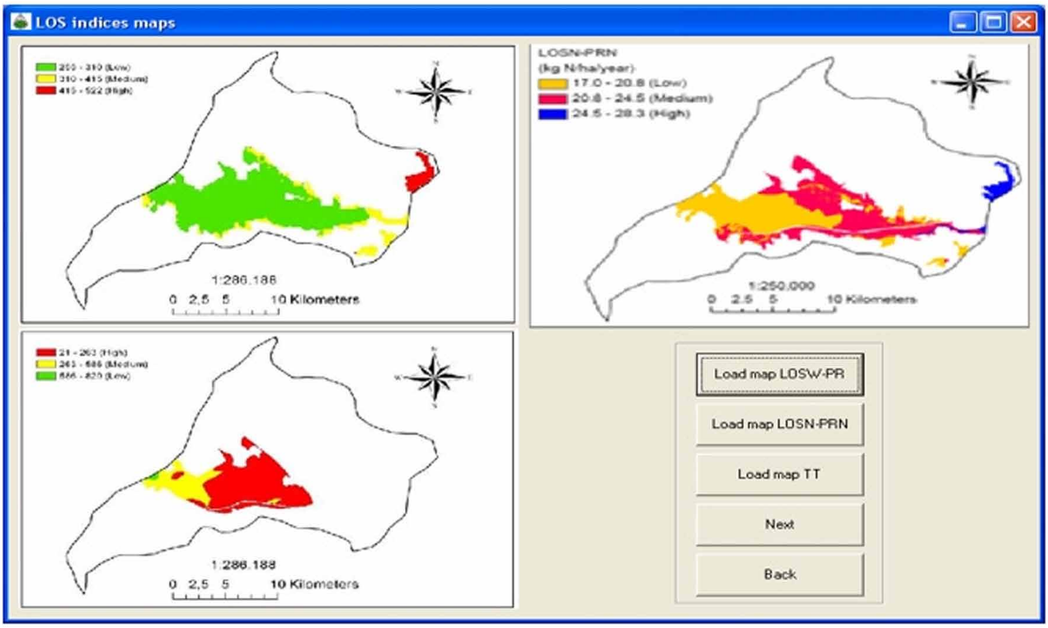


Figure 5. Deviations of results between the existent and the optimum MCDM production plan

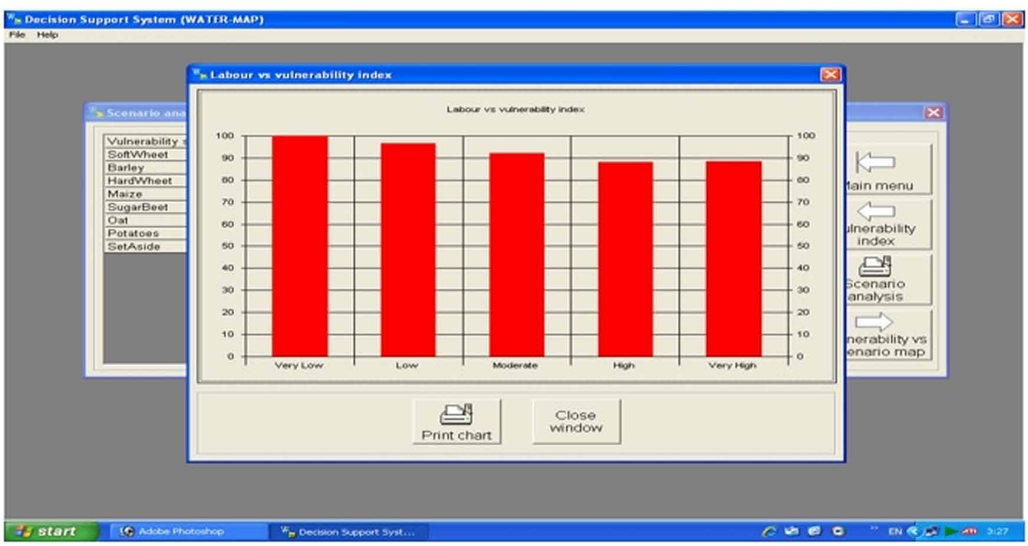
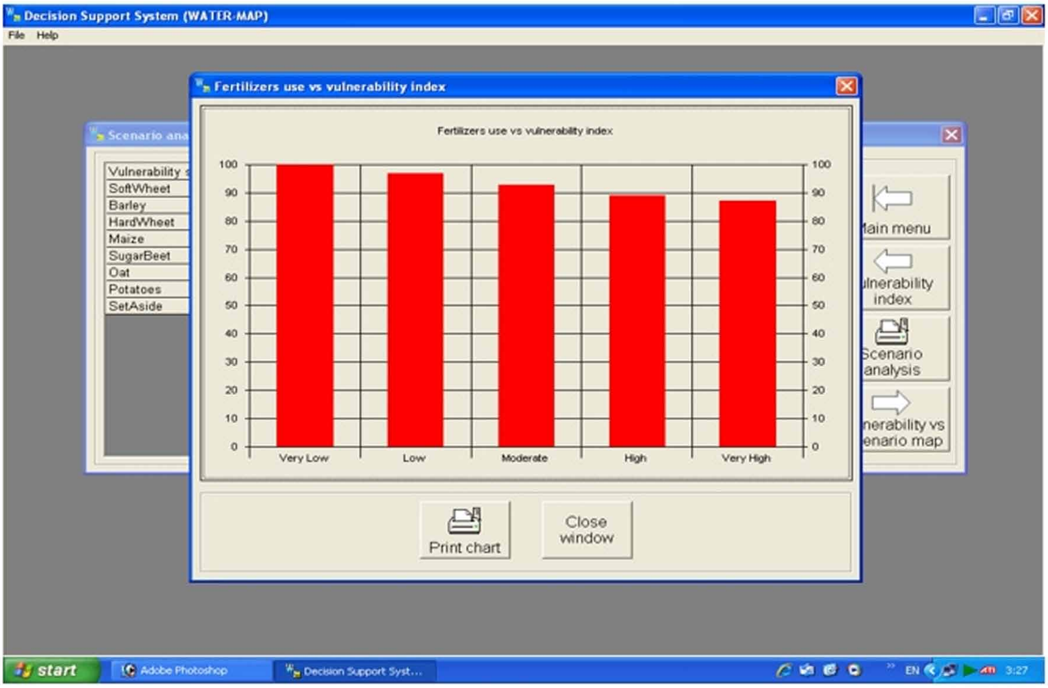


Figure 6 shows the irrigation water demand for the optimum crops plan in the study area, related to irrigation water prices. It can be stated that the price of water highly affects the type of crop that will be used; low water prices imply high water-consumption crops and as prices increase irrigated crops are replaced by non-irrigated ones.

Figure 6. Irrigation water demand of the average farm in relation to water price



5. OTHER DSS APPLICATIONS

As it was mentioned in the section of Introduction, the authors are of the belief that DSSs should not be developed for a one-time use; they should be adapted and used in different contexts. For that reason, in this section, indicative, summary results of three more DSSs are presented, applied for agricultural production planning and environmental protection in different regions of Greece under additional specific objectives and constraints. These DSSs were developed using the same philosophy and core modules as the one presented above.

5.1. A DSS For Planning of Agricultural Production in Serbia Region, Northern Greece

The particular DSS is based on the development possibilities of a Serbia region and aims at its development by making better use of the available production resources and the existing agricultural industries. The DSS used the linear programming and the goal programming module to propose alternative production plans for different goals, which optimize the management of all the available production factors.

The alternative production plans achieved a better utilization of the existing processing agricultural industry or propose its extension, taking into account the supply and demand of agricultural products in the study area. Figures 7 and 8 are two typical screens of this DSS that show, the yields, costs and profits of the optimum LP production plan (Figure 7), and, the variations in labor productivity relative to the man-units used (Figure 8). The detailed description of this DSS can be found in (Papathanasiou et al., 2005).

Figure 7. Returns, expenses and profits of the optimum LP production plan

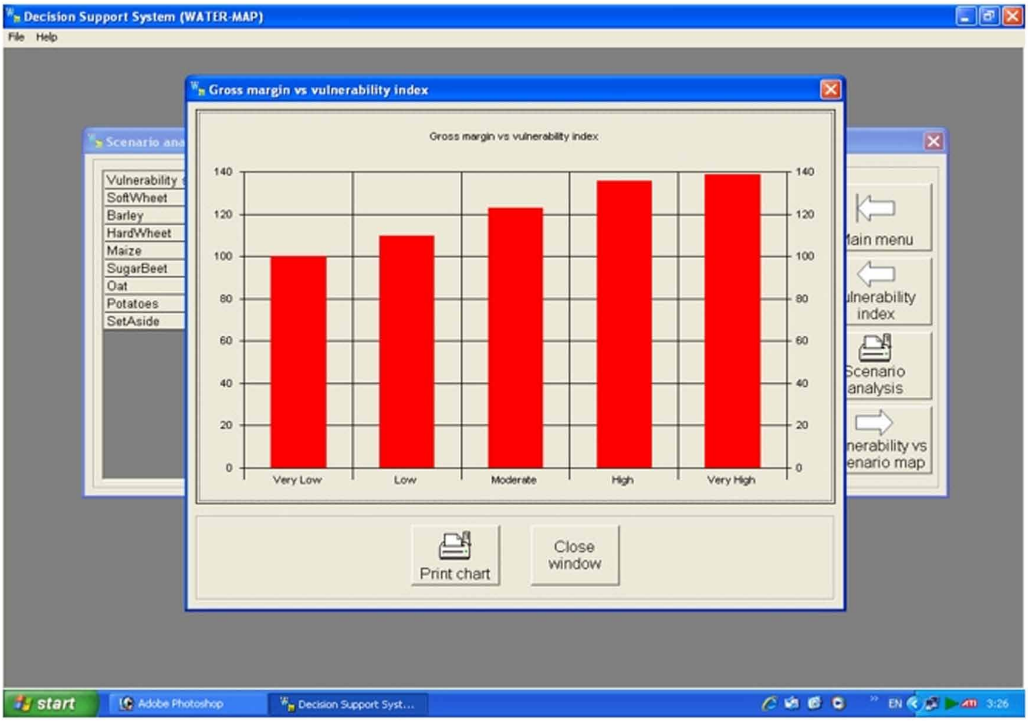
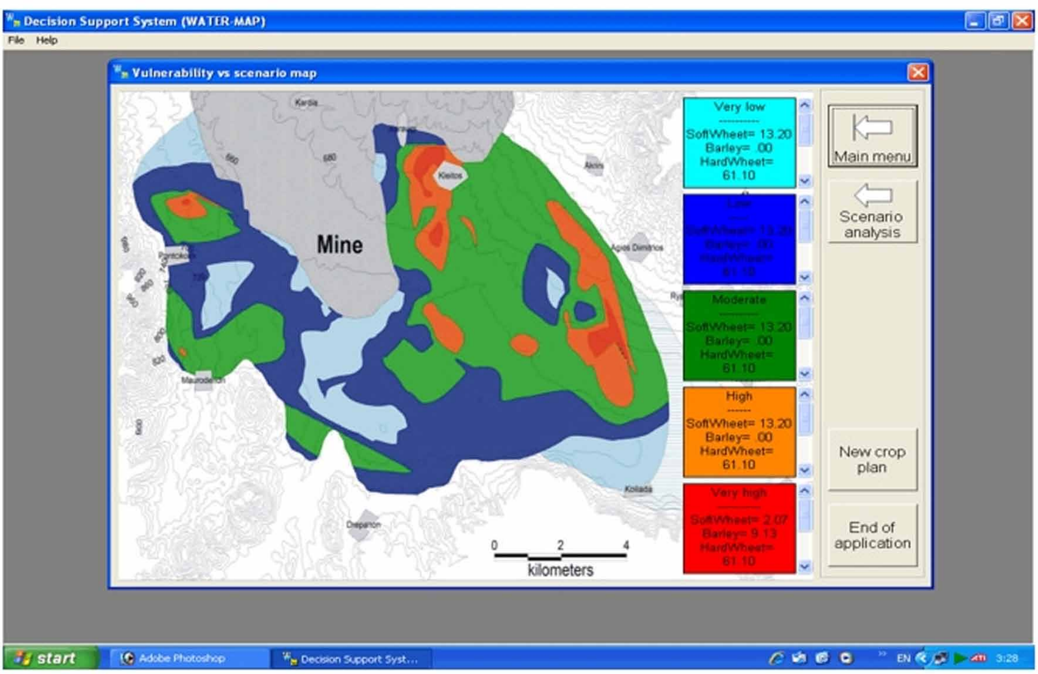


Figure 8. Variations of labor productivity in relation to man units used



5.2. Watermap: A DSS For Sustainable Development and Environmental Protection of Rural Regions

Watermap is a DSS for the sustainable development and environmental protection of agricultural areas (in the framework of the Interreg-Archimed project WaterMap). It aimed at optimizing the production plan of an agricultural area, taking into account the available production resources, environmental parameters and the vulnerability maps of the area. The DSS used a Multicriteria Mathematical Programming Model, while the incorporation of vulnerability maps into the DSS, allowed the design of policies for optimum management of the available resources, constrained by the condition that the groundwater should be kept protected.

The DSS can be further used to simulate different scenarios and policies due to changes in social, economic, and environmental parameters. In this way, alternative production plans and uses of the agricultural land can be achieved, as well as the assessment of the economic, social and environmental impacts of different policies.

In Figure 9, the vulnerability map of the study region is presented in relation to different vulnerability scenarios, while Figures 10, 11 and 12 show the gross margin, the fertilizers use and the total labor use in relation to vulnerability scenarios. The Watermap DSS was applied in the region of Sarighol Basin in the prefecture of Kozani in Northern Greece. The detailed description can be found in (Manos et al., 2010a; Manos et al., 2010b).

5.3 EU-Water: A DSS For Planning of Agricultural Production

This DSS was developed in the framework of a South-East Europe research project. It was designed taking into account “ease-of-use” and it is based on the relevant GIS maps created with the LOS indices of water (LOSW: annual losses of water) and nitrogen (LOSN: annual losses of nitrogen) due to deep percolation beneath the root zone and to surface runoff, which were developed for the project (Figure 13). It is an important planning tool that allows regional authorities to design sustainable rural policies that could increase production efficiency in the region.

The application of the DSS optimized the production plan in the study region, taking into account the available resources (various types of cultivated land, labor and capital) and also environmental

Figure 9. Vulnerability map of the region versus different vulnerability scenarios

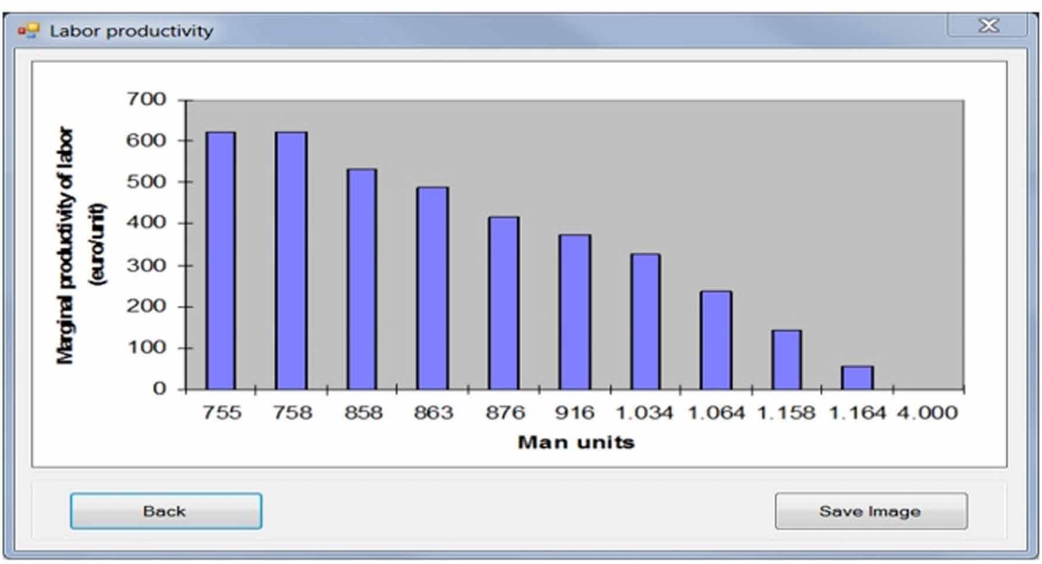


Figure 10. Gross Margin versus vulnerability scenarios

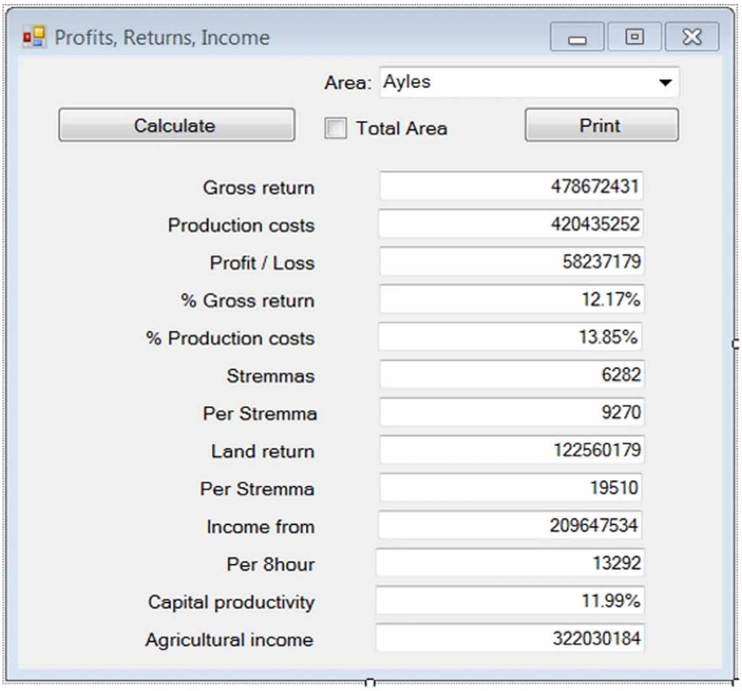


Figure 11. Fertilizers use versus vulnerability scenarios

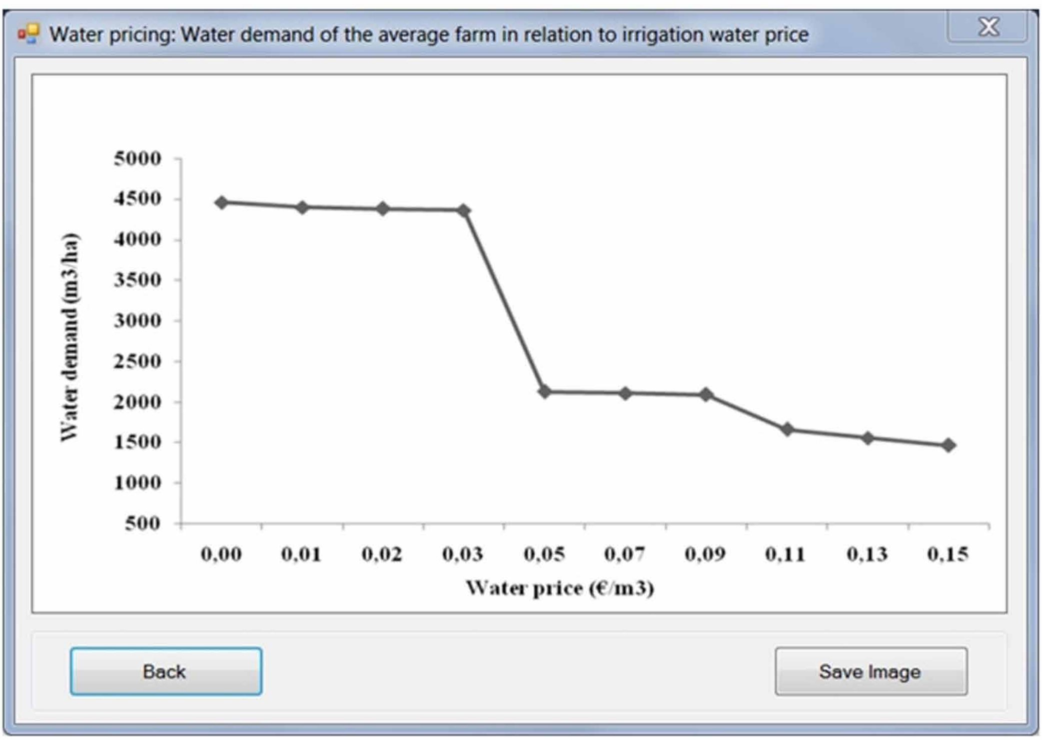


Figure 12. Total labor use versus vulnerability scenarios

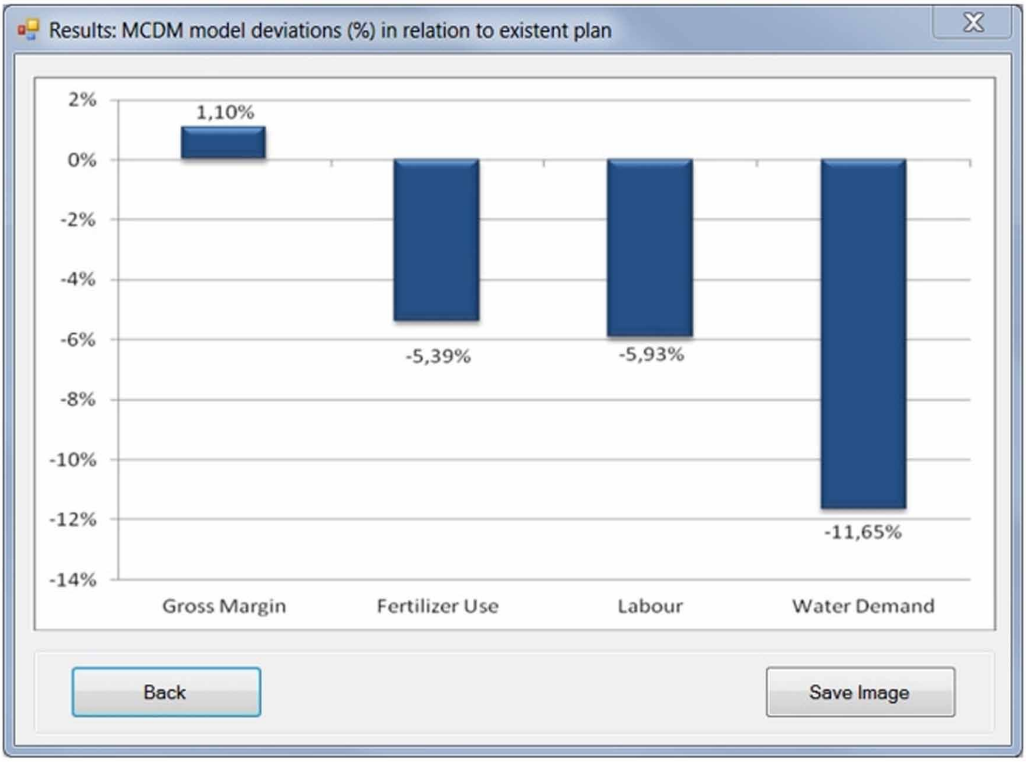
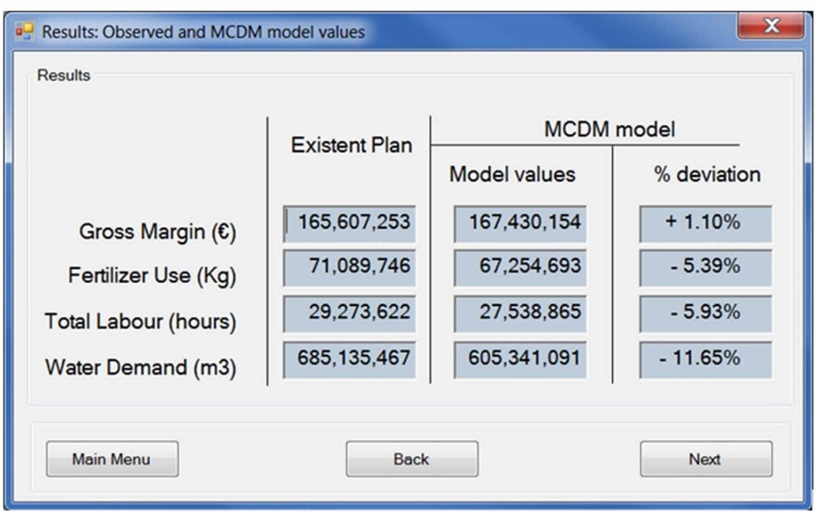


Figure 13. LOS Indices Maps



parameters (reduction of nitrates, irrigation water consumption, etc.). The DSS can be further used to simulate different scenarios by varying social, economic and environmental parameters (e.g. different nitrate levels or irrigation water consumption per crop) (Figure 14). The EU-Water DSS uses a Multicriteria Mathematical Programming model and it was applied in the region of Sarighol Basin in prefecture of Kozani in Northern Greece. The detailed description can be found in ().

6. CONCLUSION

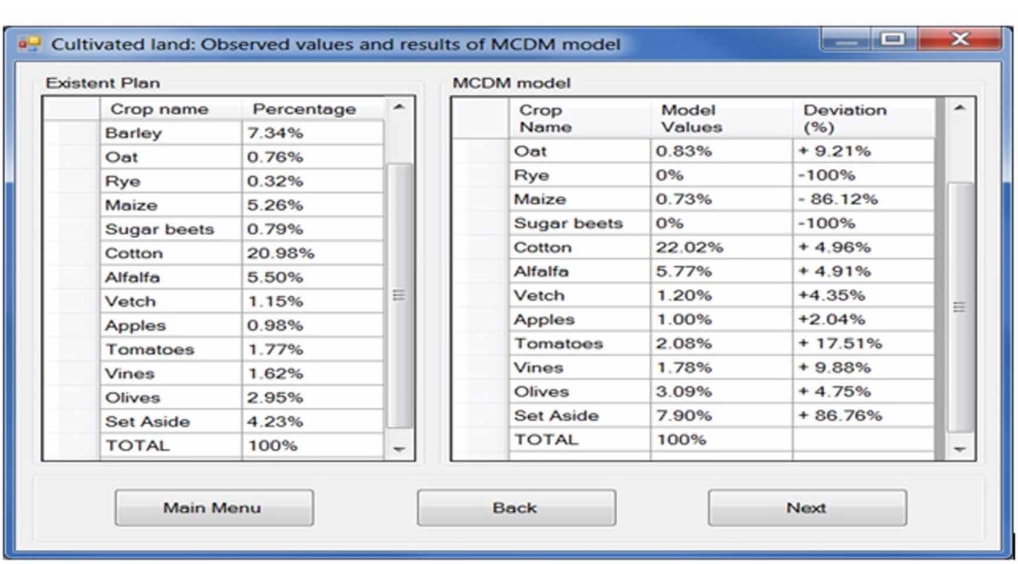
Decision Support Systems are important tools in the decision-making process in the context of agricultural production of a region. DSSs can propose a series of optimum production plans while taking into account constraints on the cultivated land, labor and capital. Decision makers can also use them to perform scenario analyses, under different combinations of socioeconomic and environmental parameters and gain insights into the economic, social and environmental consequences of their policies.

The purpose of the present chapter was to present the application of such a DSS in the prefecture of Larissa and the application of other DSSs across Greece. The main purpose of these agricultural DSSs is to indicate different production plans with different crops combinations that can be more effective and sustainable than the existing ones. The proposed production plans allow for increase of the gross margin, in combination to the reduction of irrigation water and nitrate fertilizers.

Decision-makers and policy planners could use the DSS to design policies that would take into account the socio-economic and environmental conditions of the specific region, the factors that could maximize the income, and/or minimize irrigation water consumption and/or fertilizers use, when compared to the existing production plan. Furthermore, the DSS could be used for the analysis and simulation of production plans under different scenarios related with changes in economic, social and environmental indicators, such as different prices of products and resources, different utilization rates of available resources, different measures and regulations of CAP and Rural Development Program.

The DSS does not come without its limitations. Firstly, the DSS does not include any variables/sub-systems concerning integral parts of agricultural managements such as climate and population change. Furthermore, since the system relies on the use of Multi-Criteria Decision Making methods,

Figure 14. Optimum plans versus LOS indices scenarios



Crop name	Percentage
Barley	7.34%
Oat	0.76%
Rye	0.32%
Maize	5.26%
Sugar beets	0.79%
Cotton	20.98%
Alfalfa	5.50%
Vetch	1.15%
Apples	0.98%
Tomatoes	1.77%
Vines	1.62%
Olives	2.95%
Set Aside	4.23%
TOTAL	100%

Crop Name	Model Values	Deviation (%)
Oat	0.83%	+ 9.21%
Rye	0%	-100%
Maize	0.73%	- 86.12%
Sugar beets	0%	-100%
Cotton	22.02%	+ 4.96%
Alfalfa	5.77%	+ 4.91%
Vetch	1.20%	+4.35%
Apples	1.00%	+2.04%
Tomatoes	2.08%	+ 17.51%
Vines	1.78%	+ 9.88%
Olives	3.09%	+ 4.75%
Set Aside	7.90%	+ 86.76%
TOTAL	100%	

concerns could be raised on why the use of these particular methods and not others. This issue is undergoing rigorous research in the field and until a definitive answer is provided, these criticisms can act in a deterrent way regarding the use of the DSS. Also in that aspect, the value of the DSS could greatly improve by a "learning" module that would teach end-users to properly use it.

All these aspects are future directions of research that the authors currently pursue, Furthermore, future research directions could include the incorporation of new modules (such as additional data sets, new models and interfaces), steps that can increase the sustainability of the DSS. Moreover, an automated interpretation of the results would increase the user-friendliness of the tool and finally, the development of a smart phone application of an existent DSS is also one important challenge of research.

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Jason Papathanasiou is an Associate Professor at the Department of Business Administration, University of Macedonia, Greece. He holds a PhD in Operational Research and a degree in Physics from the Aristotle University of Thessaloniki. He has worked for a number of years at various institutes and has organized and participated in a number of international scientific conferences and workshops. He has published papers in international scientific peer referred journals like the Environmental Monitoring and Assessment, Regional Studies, European Journal of Operational Research, PNAS, Fuzzy sets and Systems, and has edited or authored a number of books. He has participated and coordinated many research projects in FP6, FP7, Horizon 2020, Erasmus+, Interreg and COST; he was also a member of the TDP Panel of COST. His research interests include Decision Support Systems, Operational Research and Multicriteria Decision Making.

Thomas Bournaris is an Assistant Professor in the Department of Agricultural Economics at the Aristotle University of Thessaloniki, Greece. He received his BSc in Agricultural Economics from the School of Agriculture and MSc in Agricultural Economics both from Aristotle University of Thessaloniki. He works and has interests in agricultural economics, farm management and regional planning, sustainability in agriculture and management of Agricultural resources. He received his PhD from the Department of Agricultural Economics of the Aristotle University of Thessaloniki. His recent publications include papers in Energies Journal, the Journal of Environmental Management, Land Use Policy, New Medit and Environmental Monitoring and Assessment.

Basil Manos is an emeritus professor of the Department of Agricultural Economics of the Aristotle University of Thessaloniki (AUTH), Greece. His research interests are in farm management and regional planning, environmental management, impact assessment, sustainability, and efficiency, DSS and ICT in agriculture. He has studied mathematics, economics, operational research, and agricultural economics in AUTH and London School of Economics. He has conducted research in many national and European funded projects. His recent publications include papers in Regional Studies, Journal of Policy Modelling, British Food Journal, Journal of Environmental Planning and Management, Land Use Policy, Environmental Monitoring and Assessment, Environmental Impact Assessment Review, Proceedings of National Academy of Sciences, Journal of Environmental Management, and International Journal of Agricultural and Environmental Information Systems.