Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2015.1058727

57 (2016) 11484–11493
May

Taylor & Francis
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Improving the eco-efficiency of an agricultural water use system

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Received 30 January 2015; Accepted 25 May 2015

ABSTRACT

During the last two decades, the concept of eco-efficiency has been recognized as a suitable measure of progress towards a greener and more sustainable economy. The prefix "eco-" refers to both economic and ecological (environmental) performance. The need for improving eco-efficiency leads to the challenge of identifying the most promising alternative solutions which improve both the economic and the environmental performance of a given system ("eco-innovations"). Therefore, it becomes critical to develop eco-efficiency metrics for measuring environmental and economic performance of a system. The current paper presents a methodological framework that attempts to explore the use of eco-efficiency indicators in meso-level water use systems and through them to assess the impact of innovative technologies in such systems. The assessment of the environmental performance follows a life cycle-oriented approach using the midpoint impact categories while the economic performance is measured using the total value added to the product due to water use. The eco-efficiency is expressed as the ratio of the economic performance indicator to the environmental performance indicator. The proposed approach is applied to a water use system of the agricultural sector, and more specifically to the fresh form tomato crop production in Phthiotida. The analysis reveals that the most important environmental impacts of the system are (a) greenhouse gas emissions due to energy consumption, (b) release of toxic substances, due to the use of fertilizers and pesticides, and (c) depletion of freshwater resources. Three alternative interventions are examined for upgrading the value chain: (a) installation of subsurface drip irrigation (SDI) system, (b) replacement of diesel pumps with solar pumps, and (c) use of organic fertilizers. Based on the findings, all of the proposed interventions have a positive impact on the overall eco-efficiency of the system. SDI is the least favorable mainly due to its high investment cost. The use of solar pumps strongly influences climate change and photochemical ozone formation while the use of organic fertilizers has a more balanced impact on all indicators, with an emphasis on eutrophication. Thus, for a more holistic approach, regarding the eco-efficiency performance, a combined application of these three scenarios may be proposed.

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Presented at the 12th International Conference on Protection and Restoration of the Environment (PRE XII)
29 June–3 July 2014, Skiathos Island, Greece

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Keywords: Eco-efficiency; Water use systems; Agricultural sector

1. Introduction

The term eco-efficiency was introduced in the late 1980s and appeared in academic literature for the first time in 1989 [1]. An official definition was given by the World Business Council for Sustainable Development in 1991 and combined the concepts of economic welfare and competitiveness with the ecological impact of products throughout their life cycle, the use of natural resources, and the environmental carrying capacity [2]. Since then, several definitions have been proposed [3], and several studies on eco-efficiency assessment have been carried out on a company [4], business unit [5], or specific product [6,7] level. Their main objective was to support and to guide investment and management decisions in order to achieve maximized profit with minimized environmental impacts.

OECD [8] has defined eco-efficiency as the efficiency with which ecological resources are used to meet human needs and expressed it as the ratio of an output (the value of products and services produced by a firm, sector or economy as a whole) divided by the corresponding input (the sum of environmental pressures generated by the firm, the sector or the economy). This definition is more generic and has moved the concept of eco-efficiency outside the business context. Since then, eco-efficiency has become an important concept of environmental decision-making, serving both as a policy objective and as a measure of progress towards sustainability, and has been closely linked to eco-innovation. It has been applied widely at the macro- and the meso-level, either focusing on the regional [9,10] and national level [11,12] or on a specific sector of economic development [13,14].

An eco-efficient agricultural system will produce “more food from less nature” and promote sustainable growth while ensuring sufficient amount of food production. In 2002, the European Environmental Agency has assessed the eco-efficiency of agriculture on a European level, using a set of nine indicators [15]. The study showed that agricultural eco-efficiency was improving slowly and highlighted that the most important environmental concerns are the increased use of fertilizers and pesticides as well as the emissions of acidifying substances, particularly ammonia.

The need for sustainable agriculture arises from its significance to the humanity and the fact that agricultural sector has substantial environmental impact. Improvement of eco-efficiency in agriculture may be achieved through various ways. Hiltunen [16] suggested *in situ* interventions, such as plant breeding, smart cultivation, replacement of fossil fuel with renewable energy, and reuse and recycle. De Jonge [17] implied the need for change at a policy level by adopting integrated pest management, sustainable land management practices, and sustainable crop selection. However, the difficulty in assessing the eco-efficiency of an agricultural system lies in two factors. Firstly, the various characteristics and the local/regional circumstances make it difficult to adjust simulation models even between similar crops or regions and to adopt data from the literature. Furthermore, the crop yield depends on many inherent imponderables such as water availability, soil’s composition, and climate conditions that affect the eco-efficiency performance in a non-predictable, and often nonlinear, way [18].

Several methodologies have been developed and applied to the estimation of the eco-efficiency of a crop or the agricultural sector in a region. De Jonge [17] focused on enhancing the understanding of eco-efficiency, eco-innovation, and sustainable agriculture, by applying product-oriented life cycle assessment (LCA) methods. The functional unit is the amount of pesticide needed to treat one hectare of citrus crop. Eco-efficiency is defined as the ratio of the served function, expressed in hectares treated for the certain disease in a certain time, and the environmental impact, expressed in primary energy consumption and three toxicity related indicators. The analysis was applied in a citrus grove in Florida by comparing two types of fungicides suitable for this crop’s parasites, and concluded that the more innovative type of fungicide will improve the eco-efficiency of the system compared to the conventional one. Hiltunen [16] examined the temporal variation in the eco-efficiency performance of the agricultural sector of Kymenlaakso, an industrial region in Southern Finland, from 1995 to 2000. Eco-efficiency is defined as the ratio of the sectoral gross value added divided by eight alternative environmental indicators, expressing energy use, land use, greenhouse gas (GHG) emissions, acidifying substances, pesticides and fertilizers consumption, and tropospheric ozone precursors. The results showed that the overall eco-efficiency of the sector has been improving between 1995 and 2000, but it is mentioned that this is due to the higher added value. The results of this study reflect the volatile nature of the agricultural sector and the fact that its performance is affected by the climate conditions. Gómez-Limón et al. [19] use Data Environmental Analysis (DEA) in order to assess the eco-efficiency of olive farming in the rural areas of Andalusia, Spain, based on the answers from 292 local farmers, collected through a questionnaire. The economic performance is assessed using the net income per hectare, while six indicators have been used to measure the environmental pressures: erosion, biodiversity, pesticide risk, water use, nitrogen ratio, and energy ratio. The objective of the study is to maximize the ratio between the farm production and a weighted sum of inputs, both variable and fixed. The results of the analysis showed that farmers tend to use eco-inefficient management practices, mainly due to widespread technical inefficiency. Furthermore, the traditional plain growing system proved to be the most eco-efficient production system. Finally, it was verified that soil and climatic conditions strongly influence the eco-efficiency of the system.

The methodological framework, presented in the current paper, examines an agricultural system from a different point of view and follows a systemic approach and its objective is to assess alternative technological interventions, which may improve the eco-efficiency of the overall system. The system examined is a meso-level water use system and combines the water supply chain with the corresponding water use chain. It incorporates a specific water use with all the processes needed to render the water suitable (both qualitatively and quantitatively) for this use, and the treatment and discharge of the generated effluents to the environment. It considers the whole water cycle of the analyzed system by monitoring the water from its source to the final user and back to the environment.

2. Methodology

Eco-efficiency assessment is a quantitative tool which enables the study of the environmental impacts of a product or service system along with its added value. According to the ISO for the eco-efficiency assessment of product systems [20], the environmental impacts should be assessed using a LCA approach while the value of the product or service system may be chosen to reflect its resource, production, delivery or use efficiency, or a combination of these. Consequently, an eco-efficiency assessment shares with LCA many important principles and approaches such as life cycle perspective, functional unit, life cycle inventory, and life cycle impact assessment and the overall procedure generally comprises five steps [21]:

(1) Goal and scope definition;
(2) Environmental assessment;
(3) Value assessment;
(4) Quantification of eco-efficiency; and
(5) Interpretation.

2.1. Goal and scope definition

The objective of the developed methodology is to assess the eco-efficiency of a meso-level water use system. Before selecting and calculating the eco-efficiency indicators (EEI), the boundaries and the characteristics of the studied system, as well as the functional unit, have to be identified. A generic meso-level water use system can be represented as a network of unit processes. Each process represents an activity, implementing one or more technologies, where generic materials (water, raw materials, energy, and other supplementary resources) are transformed into products, while releasing emissions to the environment (air, land, water) or into the system water flow.

The boundaries of the studied system encompass all the processes related to the water supply and the water use chains and can be grouped into four generic stages, as depicted in Fig. 1. The functional unit sets the scale for the comparison of two or more products or services delivered to the consumers [8,22]. The main purpose of a functional unit is to provide a reference to which results are normalized and compared. Possible functional units for a meso-level water use system could be: (a) one unit of product/service delivered or (b) one unit of water used.

2.2. Environmental assessment

The assessment of the environmental performance follows a life cycle-oriented approach using midpoint impact categories, which make it possible to characterize different environmental problems, such as climate change, ozone depletion, photochemical ozone formation, acidification, eutrophication, and resource depletion [23]. Towards that end, an inventory of flows entering and leaving every process in the system is created and, based on that, the significance of potential environmental impacts is evaluated. The results of the inventory, expressed as elementary flows, are assigned to impact categories according to the contribution of the resource/emission to different environmental problems, using standard characterization factors. The environmental impact for impact category c is expressed as a score (ES_c) in a unit common to all contributions within the category. It can be easily

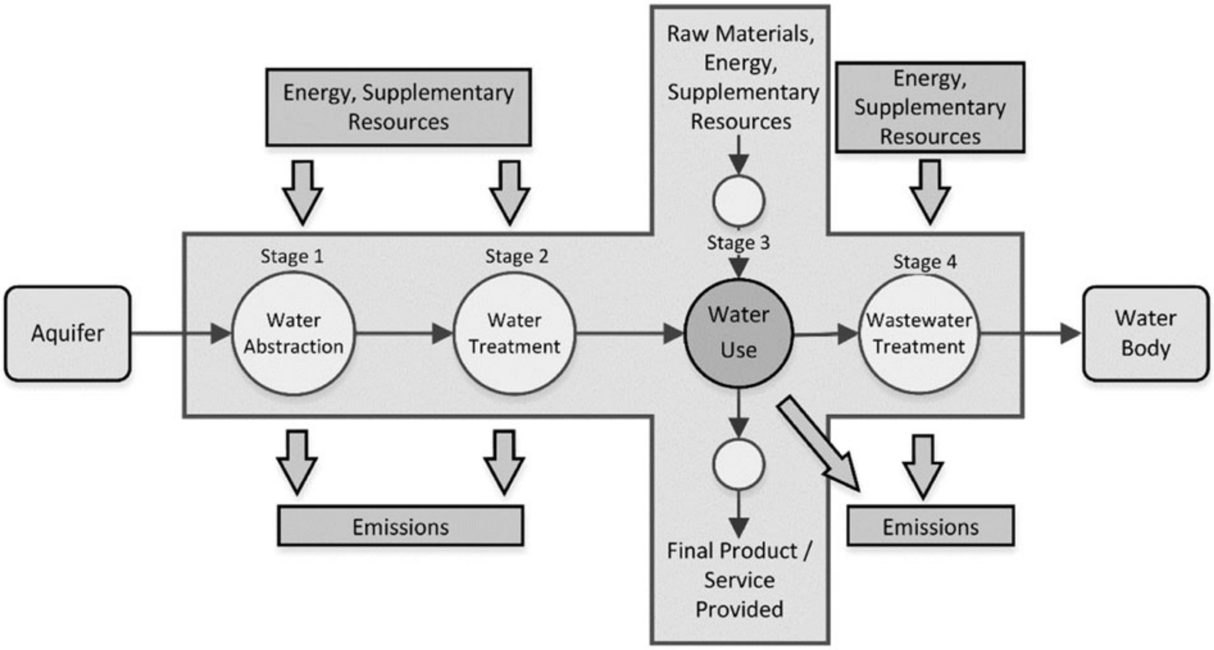

Fig. 1. Generic meso-level water system.

calculated using the flows from the inventory analysis and the characterization factors as follows:

$$\mathrm{ES_C} = \sum_{\mathrm{r}} cf_{\mathrm{r,c}} \times f_{\mathrm{r}} + \sum_{\mathrm{e}} cf_{\mathrm{e,c}} \times f_{\mathrm{e}} \tag{1}$$

where $cf_{\mathrm{r,c}}$ is the characterization factor of resource r for the impact category c, $cf_{\mathrm{e,c}}$ is the characterization factor of emission e for the impact category c (both retrieved from LCA databases), and f_{r}, f_{e} the elementary flows of resource r and emission e respectively.

Most LCA studies and databases neglect the impacts from the use of freshwater [24] and there is no standardized environmental midpoint indicator for the freshwater resource depletion [22]. However, since water consumption is a main component of the studied system, freshwater depletion cannot be neglected. The methodology proposed by Mila i Canals et al. [25] and suggested by JRC [22] is used, and it is based on the Freshwater Ecosystem Impact (FEI) indicator, defined as:

$$\mathrm{FEI} = f_{\mathrm{W,abs}} \times \mathrm{WTA} \tag{2}$$

where $f_{\mathrm{w,abs}}$ is the flow of freshwater abstracted and WTA is the water withdrawal to availability ratio.

2.3. Value assessment

The economic performance of the system is measured using the total value added (TVA) to the product due to water use, expressed in monetary units per period and per functional unit. It is estimated as:

$$\mathrm{TVA} = \mathrm{EVU} + \mathrm{VP_{BP}} - \mathrm{TFC_{WS}} - \mathrm{TFC_{WW}} - \mathrm{FC} \tag{3}$$

where EVU is the total economic value from water use, $\mathrm{VP_{BP}}$ is the income generated from any byproducts of the system, $\mathrm{TFC_{WS}}$ is the total financial cost related to water supply provision for rendering the water suitable for the specific use, $\mathrm{TFC_{WW}}$ is the total financial cost related to wastewater treatment, and FC is the annual equivalent future cash flow generated by the introduction of new technologies in the system. The total economic value from water use refers to the total benefits from direct use of water. It can be estimated using the residual value approach by subtracting the expenses for all the non-water inputs as well as the costs related to emissions in the water use stage from the total value of the products.

2.4. Eco-efficiency indicators (EEI)

The EEI of the meso-level water use systems are defined as the ratio of the economic performance indicator (TVA) to the environmental performance indicators of the system (environmental score, ES). Numerous EEI can be defined, one for each environmental impact category *c*:

$$\mathrm{EEI_C} = \frac{\mathrm{TVA}}{\mathrm{ES_C}} \tag{4}$$

EEI do not depend on the functional unit considered and an increase in the value of the indicator indicates an improvement of the overall system's eco-efficiency. An appropriate set of EEI should be selected for each system and tailored to the goal and scope of the analysis.

3. The case of fresh form tomato crop in Phthiotida

The proposed approach is applied to the agricultural sector, and more specifically to the fresh form tomato crop production in Phthiotida. The objective is to identify the environmental weaknesses of the examined system and to propose alternative actions which will improve its overall eco-efficiency. Phthiotida is a regional unit of Greece located in the administrative region of Central Greece. Geographically, it is surrounded by several mountain ranges and is part of the valley of River Spercheios. Due to its morphology, the regional climate varies between the northern and the southern part. The arable land is characterized by lowland continental conditions (hot and dry summer-mild and wet winter).

Tomato is one of the most widely grown vegetables in the world. It is a seasonal vegetable, cultivated in the summer, which requires large volumes of water and systematic irrigation at regular intervals, especially after the fruit set. Although tomato can be grown in any type of soil and is tolerant to high temperatures (up to 38°C), its sensitivity in parasites and potential diseases suggests the systematic implementation of pesticides and fertilizers. In Greece, 11.9% of the annual fresh form tomato crop is produced in Central Greece and more specifically 5% is produced in Phthiotida [26]. The term "fresh form" implies that the product is consumed, without any further processing, after the fruit has set.

3.1. System boundaries and functional unit

The total surface area dedicated to open-grown fresh form tomato cultivation in Phthiotida is 660 hectares, with an expected annual production of around 20,000 tons of tomato [26]. The studied system consists of a smaller farm with an overall area of 2 hectares. The schematic representation of the system is illustrated in Fig. 2 and consists of two different chains, the water supply chain and the tomato production chain, which are intersected at the irrigation process. Each process is represented by a node, the black solid arrows represent the water supply chain, the black dotted arrows the tomato production chain, the gray solid arrows all the incoming supplementary resources (i.e. diesel, fertilizers and pesticides) and the gray dotted arrows all the outgoing pollutants. The functional unit depends on the reference flow selected each time. In this study, two different cases are investigated: (a) when the unit of product delivered is the flow of interest, the functional unit is defined as 1 ton of tomato and (b) when the quantity of interest is the water used for the production purposes then the functional unit is 1 m^3 of water used in the production of each crop.

3.2. Environmental assessment

The average tomato yield is estimated to be 37.5 tons per hectare and the annual crop water requirements are assumed to be 7,133 m^3 per hectare [27,28]. For the farm irrigation, a drip irrigation system is used, with average field efficiency of 80%. It is also assumed that each ton of tomato requires 24 kg of fertilizer 20-20-20 and 0.4 kg of pesticide [27]. Water is abstracted using diesel pumps with a specific consumption of 0.035 L per m^3 of water. The environmental performance of the system is assessed through eight environmental impact categories relevant to the agricultural sector. The characterization factors included in the CML-IA database are used for the calculation of the environmental impacts [23]. The results of the environmental assessment are presented in Table 1.

3.3. Value assessment

The TVA to the tomato from the use of water is calculated based on the unit costs of supplementary resources, which were provided by the local suppliers. The average price of fertilizer 20-20-20 is 23.4 €/kg while the two different pesticides used cost 49.9 €/kg (Dual Gold 96) and 14.4 €/kg (Stomp 330). Furthermore, the tomato seed costs 0.32 €/g and the average price of diesel for the regional unit of Phthiotida in 2013 is 1.95 €/l. In addition, the fixed and the variable water supply cost in Phthiotida is 14.8 €/year and 1 €/m^3, respectively. Finally, according to the Greek Ministry of Development and Competitiveness, the average unit price of fresh form tomato was 1.87 €/kg

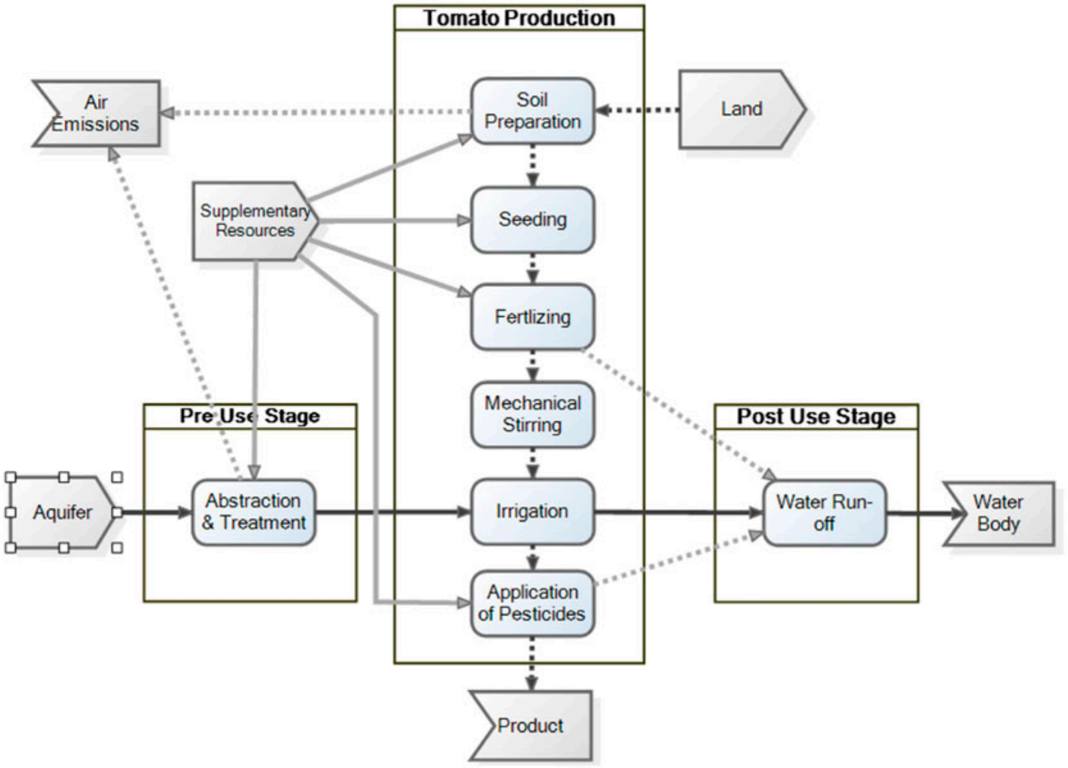

Fig. 2. Stages of water value chain and tomato crop.

Table 1
Environmental and eco-efficiency indicators for baseline scenario

Midpoint impact category	Unit	ES_c (in Unit/m^3)	ES_c (in Unit/tn tomato)	EEI_c (in €/Unit)
Climate change	$kgCO_{2,eq}$	0.225	48.21	25.8
Eutrophication	$kgPO_4^{3-}{}_{,eq}$	0.021	4.52	275
Acidification	$kgSO^{2-}{}_{,eq}$	<0.001	0.07	18,928
Photochemical oxidation	$kgC_2H_{4,eq}$	<0.001	0.012	99,760
Human toxicity	$kg1,4DCB_{,eq}$	0.002	0.37	3,334
Freshwater ecotoxicity	$kg1,4DCB_{,eq}$	0.178	38	32.8
Terrestrial ecotoxicity	$kg1,4DCB_{,eq}$	<0.001	0.011	115,407
Freshwater depletion	m^3	0.188	40.12	31.1

in 2011. The TVA to the product from the water use is 1.25 €/kg of tomato or 5.82 €/m^3 of water used.

3.4. *Eco-efficiency assessment*

Based on the environmental and value assessment, the eight relevant EEI are calculated and presented in Table 1. It is apparent that the three major environmental impacts of the studied system (highlighted by the indicators with the highest ES and the lowest eco-efficiency value) are: (a) climate change, due to diesel consumption for water abstraction and soil preparation, (b) freshwater depletion, (c) freshwater ecotoxicity, and (d) eutrophication due to the use of pesticides and fertilizers respectively. Comparing two other agricultural regions that were examined using the same approach, the Monte Novo irrigation perimeter in Portugal and the Sinistra Ofanto irrigation scheme in Italy, the main environmental impacts identified are identical; climate change, eutrophication, and freshwater resource depletion [29]. The differentiations in the indicators' values can be explained by the different crop patterns (with varying water requirements), the fuel mix used in each region, and the different systems boundaries for the analysis.

Thus, the upgrading of the system through innovative technologies should aim at improving these four key indicators. Towards that end, three alternative options will be examined:

(1) More efficient irrigation, by installing a sub-surface drip irrigation (SDI) system
(2) Substitution of fossil fuels with renewable energy sources, by replacing diesel pumps with solar ones
(3) Promotion of agro-ecological practices and soil management techniques, using organic fertilizers instead of conventional

4. Value chain upgrade

4.1. Installation of an SDI system

A common practice towards improving water use efficiency of an irrigation scheme is to replace gravity-fed irrigation systems, such as border check and furrow, with more efficient pressurized systems [30,31], as they may offer a significant reduction in water use at the field scale. Drip irrigation systems (either surface or sub-surface) use point sources in order to achieve slow and precise application of water and nutrients directly to the root zones in a controlled flow that satisfies the maximum crop irrigation requirements.

More specifically, SDI systems supply water to crops through buried plastic drip lines with emission points. Water is delivered underground at the depth where most of the rooting system reside and thus, minimization of wetting soil surface, weed generation, and surface evaporation can be achieved. Furthermore, in case of an SDI system, the tubes can be left in place for multiple seasons. According to plot and field applications conducted by the Water Management Research Laboratory, and reviewed by Ayars et al. [32], the application of SDI, resulted in significant yield and water use efficiency in tomato, cotton, sweet corn, alfalfa, and cantaloupe. Furthermore, Phene et al. [33] presented significant yield increases in tomatoes cultivation using high-frequency SDI and precise fertility management. The major disadvantages of such systems are the higher investment and management costs than conventional irrigation systems [34]. It is assumed that the investment cost of the application of an SDI system in the examined irrigated field is 5,000 €/ha, its annual operation and maintenance cost is equal to 12% of the investment cost, its lifetime is 15 years. After its implementation, the average field efficiency increases up to 90% and a 20% yield increase can be achieved.

4.2. Substitution of fossil fuels

The use of renewable energy is attractive for water pumping applications, especially in rural and remote areas or isolated systems, not connected to the electricity grid. More specifically, the use of the solar radiation as a power source for irrigation is highly recommended for rural farms without existing power lines as it is available at the site of application without the employment of a distribution system. Solar photovoltaic (PV) water pumping systems can be the most cost-effective pumping solution when they are designed and sized properly in order to take advantage of the solar energy as efficiently as possible [35]. PV pumps are more economical, mainly due to the lower operation and maintenance costs compared to a diesel pump, and have less environmental impact than pumps powered by fossil fuels [36]. Furthermore, they can be easily installed at the site of use, without needing long pipelines, and they are considered to be highly reliable and durable [37].

Plant water demand and the quantity of water pumped by a photovoltaic-powered water pumping system are both directly correlated to daily solar insolation [35]. The average annual sun radiation in Greece is estimated at 1,800 kWh/m^2 [38] while for the regional unit of Phthiotida, the monthly average solar radiation is 140 kWh/m^2 [39]. Assuming an average overall efficiency of the PV panel of 10%, the required installed PV capacity for satisfying the daily irrigation requirements of 1 hectare of tomato is estimated at 9 kW. The installation cost of such system is estimated to be around 2,000 € [40] and the annual operation and maintenance costs are 200 €/year.

4.3. Application of organic fertilizers

The shift from traditional agricultural to modern organic production methods will have significant social, economic, and environmental benefits. More specifically, an organic agricultural system is characterized by reduced environmental impact, improved products quality as well as improved process effectiveness through enhancing water use efficiency and reducing the use of synthetic fertilizers, pesticides and herbicides [41]. Organic farming will thus contribute to the conservation of natural resources, the maintenance of biodiversity, and the preservation of the ecosystem. One of the common practices towards organic farming is the application of organic fertilizers

Table 2
Comparison of the eco-efficiency indicators in the four scenarios

Midpoint impact category	Unit	Baseline scenario	Sub surface drip irrigation	Solar pump	Organic farming
Climate change	$€/kgCO_{2,eq}$	25.8	35.3	66.6	46.6
Eutrophication	$€/kgPO_4^{3-}{}_{,eq}$	275	351	277	1,068
Acidification	$€/kgSO^{2-}{}_{,eq}$	18,928	25,753	48,741	34,350
Photochemical oxidation	$€/kgC_2H_{4,eq}$	99,760	135,465	256,426	178,388
Human toxicity	$€/kg1,4DCB_{,eq}$	3,334	3,894	4,476	5,393
Freshwater ecotoxicity	$€/kg1,4DCB_{,eq}$	32.8	34.8	33.0	49.3
Terrestrial ecotoxicity	$€/kg1,4DCB_{,eq}$	115,407	122,635	116,075	173,456
Freshwater depletion	$€/m^3$	31.1	44.6	31.2	56.0

or compounds to the crops, aiming at re-allocating nutrients while reducing the impacts, due to chemical substances, on human and freshwater toxicity. In 2001, OECD define organic fertilizers as fertilizers that are derived from animal products and plant residues containing sufficient nitrogen. In 2014, ECOFI proposed the definition of an organic fertilizer as a fertilizer whose main function is to provide nutrients under organic forms which consist of organic materials of plant and/or animal origin. However, the use of organic fertilizers may include higher labor, increased energy demand, and difficulty in optimizing N availability in soils with organic fertilization as well as in matching plant demand [42]. Moreover, when organic fertilizers have to be obtained off-farm, undesirable transport and distribution costs may incur.

In the studied system, the replacement of the chemical fertilizer 20-20-20 with compost produced from aerobic biological degradation of organic residues is proposed and assessed. In the Greek market, the available compost contains 1–2% N, 0.5–1% P, and 0.5–1% K, including significant quantities of minerals. The total amount of organic fertilizer required for sufficient fertilization of tomato crops is estimated to be 15–30 tn/ha and the corresponding supply cost is approximately 60–130 €/tn. The application of organic fertilizers will have a negative impact on the agricultural production, reducing the crop yield by 20%. Based on market research, in 2011, the unit price of organic tomato varied between 2.5 and 3.5 €/kg, an increase of up to 40% compared to tomato crops from conventional farming.

4.4. Technology Assessment

The TVA to the tomato due to water use increases in all three cases (8.36 €/m^3 in the SDI scenario, 5.86 €/m^3 in the solar pump scenario, 10.5 €/m^3 in the organic farming scenario compared to 5.82 €/m^3 in the baseline scenario), while the net annual economic output of the farmers remains positive. Furthermore, Table 2 presents the absolute values of the EEI for all three technology scenarios while Fig. 3 illustrates the relative change compared to the baseline scenario. All three scenarios influence positively the overall eco-efficiency of the system, by improving the majority of the eight EEI in all three cases (Table 2).

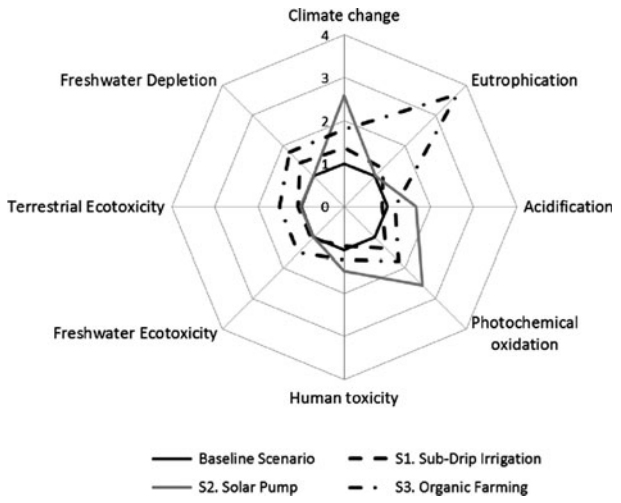

Fig. 3. Eco-efficiency assessment for the three technology scenarios.

Among them, SDI system has the worst performance since it improves only half of the indicators, with the most positive impact being on the freshwater depletion, while the other four indicators remain near the baseline values. This is mainly due to its high investment cost, which counterbalances the positive impact on the environmental performance of the system. The use of solar pumps significantly improves, as expected, all the indicators which are closely related to the fossil fuels consumption, mainly the climate change and photochemical oxidation indicators, and secondarily the human toxicity and acidification indicators. Finally, the promotion of organic fertilizers presents the overall best performance with a balanced positive impact for all the EEI, and highlighting a significant improvement regarding eutrophication indicator due to lack of toxic substances. Also, compared to the other two scenarios, it seems to be more eco-efficient in the categories of freshwater depletion and ecotoxicity. These same conclusions were also drawn from the other two Case Studies [29], where it was pointed out that pollution prevention scenarios can be more easily implemented than water saving technologies, since farmers have a positive net economic output leading to an increased eco-efficiency of the system.

5. Conclusions

The paper presents a methodological framework for the assessment of eco-efficiency in water use systems as a measure of progress towards a more sustainable economy. This approach was applied to the water use system of tomato production in Phthiotida. The baseline scenario is compared to the implementation of three alternative technology scenarios (SDI, installation of solar pumps, use of organic fertilizers) in order to improve the eco-efficiency of the system. The analysis has showed that there is a lot of room for improvement, concerning the main environmental problems of the area; namely the climate change, the freshwater resource depletion, and the eutrophication effect, due to water run-off. While each alternative affects in a different way and level the eco-efficiency of the system, all appear to improve most of the indicators. Thus, for a more integrated approach, regarding the eco-efficiency performance, a combined application of these three scenarios may be proposed. Towards that end, a combined scenario has been examined by simply assuming that all three options were implemented in 50% of the area for tomato crops in Phthiotida. In that case, a minimum reduction of GHG emissions by 10% and of freshwater abstracted by 2% could be achieved, while at the same time the TVA would be increased by 15%.

Moreover, the analysis suggests that the proposed methodological framework gives reliable results and can be expanded and applied to other water use systems. However, it should be noted that it is a methodology that does not provide the optimal solution but compares alternative system configurations, highlighting the strong and weak points of each one. Furthermore, since all the figures used, and especially the economic ones, are characterized by temporal variation and increased level of uncertainty, the analysis could be complemented by a sensitivity analysis which will allow to quantify the uncertainty and identify the most critical parameters. Finally, the application of the framework to other alternative water use systems is encouraged since this will help reveal its weaknesses as well as more areas for further research.

Acknowledgments

The methodology presented in the paper arises from 'EcoWater: Meso-level eco-efficiency indicators to assess technologies & their uptake in water use sectors', a collaborative research project of the 7th Framework Programme, grant agreement no. 282882, coordinated by the National Technical University of Athens (NTUA).

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