

1 **Life cycle assessment of the environmental performance of conventional and organic methods of**
2 **open field pepper cultivation system**

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11 **ABSTRACT**

12 *Purpose:* As the scale of the organic cultivation sector keeps increasing, there is growing demand for
13 reliable data on organic agriculture and its effect on the environment. Conventional agriculture uses
14 chemical fertilizers and pesticides, whilst organic cultivation mainly relies on crop rotation and organic
15 fertilizers. The aim of this work is to quantify and compare the environmental sustainability of typical
16 conventional and organic pepper cultivation systems.

17 *Methods:* Two open field pepper cultivations, both located in the Anthemountas basin, Northern Greece,
18 are selected as case studies. Life cycle assessment (LCA) is used to quantify the overall environmental
19 footprint and identify particular environmental weaknesses (i.e. unsustainable practices) of each
20 cultivation system. Results are analysed at both midpoint and endpoint levels in order to obtain a
21 comprehensive overview of the sustainability of each system. Attributional LCA (ALCA) is employed to
22 identify emissions associated with the life cycles of the two systems. Results are presented for problem-
23 oriented (midpoint) and damage-oriented (endpoint) approaches, using ReCiPe impact assessment.

24 *Results and Discussion:* At midpoint level, conventional cultivation exhibits about three-fold higher
25 environmental impact on freshwater eutrophication, than organic cultivation. This arises from the
26 extensive use of nitrogen and phosphorus-based fertilizers, with consequent direct emissions to the
27 environment. The remaining impact categories are mainly affected by irrigation, with associated indirect
28 emissions linked to electricity production. At endpoint level, the main hotspots identified for conventional
29 cultivation are irrigation and fertilizing, due to intensive use of chemical fertilizers and (to a lesser
30 degree) pesticides. For organic pepper cultivation, the main environmental hotspots are irrigation,

1 machinery use, and manure loading and spreading processes. Of these, the highest score for irrigation
2 derives from the heavy electricity consumption required for groundwater pumping associated with the
3 fossil-fuel dependent Greek electricity mix.

4 *Conclusions:* Organic and conventional cultivation systems have similar total environmental impacts per
5 unit of product; with organic cultivation achieving lower environmental impacts in ‘freshwater
6 eutrophication’, ‘climate change’, ‘terrestrial acidification’, and ‘marine eutrophication’ categories.
7 Conventional cultivation has a significantly greater effect on the freshwater eutrophication impact
8 category, due to phosphate emissions arising from application of chemical fertilizers.

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11 **Keywords:** sustainable agriculture; non-organic; organic farming; vegetables; environmental footprint;
12 sensitivity analysis

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1 **1. Introduction**

2 Over recent decades, organic farming has increased sharply in many parts of the world (EC, 2013, 2014;
3 Foteinis and Chatzisyneon, 2016). In Europe, a major milestone was the implementation of EC Reg.
4 2078/92, which promoted organic farming in the belief that it yields more positive ecological effects than
5 conventional farming (EC, 1998). Although organic farming is of relatively higher cost than conventional
6 farming, Europe's organic land expanded by 0.5 M ha/yr since 2005, resulting in more than 5 % of
7 European agricultural area being taken up by organic farmland (EC, 2013). The steadily increasing
8 demand for organic products derives from consumers' perceived needs for a healthier way of life; because
9 organic food is considered safer than conventionally grown products (López *et al.*, 2014). Moreover,
10 organic farming plays an important role in the EU agricultural policy framework, which assumes that
11 organic farming has minimal adverse impact on the environment (EC, 2007, 2013). As the scale of the
12 organic sector keeps increasing, there is growing demand for reliable data on organic agriculture (EC,
13 2013) and its effect on the environment.

14 Conventional agriculture uses chemical inputs, such as fertilizers, herbicides and pesticides, whilst
15 organic cultivation mainly relies on crop rotation and residues, the use of organic fertilizers, and
16 biological pest control (Stolze *et al.*, 2000; EC, 2007, 2013). As a result, it is claimed that organic farming
17 is less harmful to the environment than conventional farming (Stolze *et al.*, 2000; EC, 2013, 2014; FAO,
18 2016). However, this is a matter of debate since the higher crop yield of conventional systems could in
19 certain cases outweigh the environmental benefits per product unit of organic farming (Tuomisto *et al.*,
20 2012; Meier *et al.*, 2015; Foteinis and Chatzisyneon, 2016). On the one hand, organic agriculture claims
21 long-term sustainability by considering medium- and long-term effects of agricultural interventions on the
22 agro-ecosystem (FAO, 2016). Moreover, herbicide leachate can reduce the diversity of flora and fauna in
23 freshwater ecosystems and alter their chemical and biological quality (Laini *et al.*, 2012); whilst pesticide
24 residues in food result in high toxic exposure, about 10^3 to 10^5 times higher than that from drinking water
25 or inhalation (Margni *et al.*, 2002). Therefore, better evaluation practices for assessing pesticide residues
26 in food need to be established as a matter of priority. Organic agriculture also appears more beneficial to
27 biodiversity, but many knowledge gaps exist (Hole *et al.*, 2005). On the other hand, the main drawbacks
28 of organic farming are its higher cost (EC, 2013) and lower crop yield. Crop yield differences between
29 organic and conventional systems range from 5 to 34 %, while on average, organic cultivation can reach
30 about 80 % of the yield of conventional cultivation, but with substantial variations depending on system

1 and site characteristics (De Ponti et al., 2012; Meier et al., 2015). Consequently, it has been reported that
2 environmental impacts per area of farmed land are usually lower for organic systems, but, when related to
3 the quantity produced, the impacts could often be higher depending on the crop and local conditions
4 (Tuomisto et al., 2012; Meier et al., 2015; Foteinis and Chatzisyseon, 2016). Nonetheless, a recent
5 review article on LCA studies comparing agricultural products from conventional and organic farming
6 systems (Meier et al., 2015) reported that it is not yet possible to draw a conclusive picture on the general
7 environmental performance of the two farming systems. In this context, comparative LCAs often do not
8 adequately differentiate the specific characteristics of the two systems while basing assumed values for
9 organic systems on those for conventional agriculture (Meier et al., 2015). Crop-specific investigations
10 are therefore necessary into the relative environmental impacts of organic and conventional agriculture
11 systems. A compendium of environmental impacts would enable decision makers to implement more
12 harmonized and sustainable agricultural policies.

13 LCA is a powerful tool that quantifies environmental impacts of constituent processes and estimates the
14 overall environmental sustainability of a system, providing informed options to stakeholders including
15 decision makers, researchers, and communities. Therefore, LCA provides a reliable, complete,
16 macroscopic quantification of net environmental impacts, and so its use is steadily increasing (Foteinis *et*
17 *al.*, 2011; Chatzisyseon *et al.*, 2013). Meier et al. (2015) used LCA to compare several farm products,
18 including milk, beef, pig, poultry, arable crops, fruits, and vegetables, produced by different farming
19 systems and concluded that more comprehensive LCAs were needed to compare the environmental
20 sustainability of organic and conventional products (Meier *et al.*, 2015). To date, LCA has been used to
21 investigate the environmental impacts of various farms producing vegetables and fruits (Noponen *et al.*,
22 2012; Tuomisto *et al.*, 2012; O'Brien *et al.*, 2014; Meier *et al.*, 2015; Foteinis and Chatzisyseon, 2016;
23 Fusi *et al.*, 2016), but, to the authors' knowledge, LCA has not been applied to assess the sustainability of
24 organic and conventional pepper cultivation. Instead, emphasis has been placed on differences between
25 organic and conventional pepper fruit yield or pepper nutritive value, e.g. antioxidant and bioactive
26 composition (Del Amor, 2007; Szafirowska and Elkner, 2009; López *et al.*, 2014).

27 The aim of this paper is to compare typical conventional and organic cultivation systems used for open
28 field pepper cultivation in Mediterranean countries, in terms of environmental sustainability. The case
29 studies comprise two open field pepper cultivations, both located in the Anthemountas basin, Northern
30 Greece. LCA is used to quantify the overall environmental footprint and identify particular environmental

1 weaknesses (i.e. unsustainable practices) of each cultivation system. Results are analysed at both
2 midpoint and endpoint levels in order to obtain a comprehensive overview of the sustainability of each
3 system.

4 **2. Materials and methods**

5 **2.1 LCA software and libraries**

6 LCA analysis was undertaken using SimaPro, version 8.0.1.4 which incorporates all common life cycle
7 inventory (LCI) datasets, including ecoinvent v3.1, the European Life Cycle Database (ELCD) and the
8 industry-specific Agri-footprint database (PRé, 2014).

9 **2.2 Case study and data collection**

10
11 *Capsicum annuum* plants (Solanaceae family) include chilli peppers, bell peppers (or paprika). Such
12 plants are cultivated worldwide, with the Mediterranean countries specialising in bell peppers; an
13 example being red peppers grown in Crete, Dodekanisa, and Northern Greece, the latter notable for its
14 extended areas of organic pepper cultivation (Delioglou, 2010). The case study focuses on organic and
15 conventional Florina pepper (Φλωρίνης in Greek) cultivation in the eastern part of the Anthemountas
16 basin, Northern Greece. This is an area of traditional agriculture where a variety of vegetable crops are
17 cultivated (Andreadakis *et al.*, 2007), and soil conditions are particularly favourable for pepper
18 cultivation, with good drainage properties and pH values between 5.5 and 7.0 (Delioglou, 2010). Data
19 were obtained from a certified organic vegetable farm and a conventional pepper farm, which have been
20 operating for at least two decades, by carrying out direct interviews with farmers (Foteinis and
21 Chatzisyneon, 2016). These farms were identified by the local agriculturist as representative (i.e. inputs,
22 outputs, agricultural practices and irrigation techniques) of local conditions and therefore were selected
23 for further assessment. All farmers within the greater area work closely with the local agriculturist who
24 has an overview of the agricultural activities, crop management techniques and yield, and application of
25 pesticides and fertilizers by the farmers. Data collected at all stages of open field cultivation were then
26 processed using life cycle assessment (LCA) software.

2.3 System boundaries

Figure 1 shows the boundaries of conventional and organic pepper cultivation systems. Both systems have similar post-harvesting activities, such as packaging, transportation, sale and consumption, and so these are treated as being outside the boundaries. In each system, seedling growth occurs in a plant nursery where steady temperature and humidity conditions are maintained. By assuming similarity between the plant nurseries, seedling growth is also treated as outside the system boundaries. Therefore, LCA, starting at seedling planting and ending at pepper fruit manual harvesting, is performed for each cultivation system. A mean transportation distance of 30 km from retail to farmer is ascribed, in both systems, to all main environmentally-relevant physical flows, i.e. of manure and chemical fertilizers. Pesticides have negligible weight compared to organic and chemical fertilizers, and so the transport of pesticides from manufacturer to retailer is not included within the boundaries of this LCA. Plant nurseries are assumed to be located close to the field, and so seedling transportation is external to the boundaries. CO₂ sequestration is also considered to be external to the boundaries because, after consumption, the biogenic CO₂ fixation of pepper fruit is quickly released back to the atmosphere.

Figure 1

2.4 Functional unit

A yield of 1000 kg (1 tonne) of marketable pepper fruits is set as the functional unit, and all results are expressed per unit product. This functional unit allows for the fact that organic pepper cultivation achieves 37.5% lower production yield than conventional cultivation. In both systems, a fraction of the pepper yield is non-marketable, depending on weather conditions and pest control. This fraction is usually small and the waste product, which is of organic nature, is either disposed of or used for other purposes, such as animal feedstock. In our case studies, the farmers dispose the non-marketable yield and so this process and relevant emissions are not included within the system boundaries.

2.5 Assumptions and limitations

The present analysis is based on the following assumptions: (i) data obtained from a certified organic farm and conventional vegetable cultivation are representative of pepper cultivation in the greater area; (ii) no weather extremes occur during cultivation; (iii) average values hold for the technology considered;

(iv) energy used for irrigation purposes comes solely from the Greek energy mix; (v) a mean distance of 30 km for transporting fertilizers and pesticides to the field. The study is limited to data gathered in Northern Greece during the summer of 2015.

2.6 Life cycle inventory (LCI)

Table 1 lists the life cycle inventories (LCIs) for both cultivation systems as mean values calculated over the reference period of summer 2015, obtained from the interview data collected from farmers. It should be noted that in Northern Greece, pepper seedlings are planted in the field during spring, from early to mid-May, and plant cultivation ends in November, when the climate gets colder and light frosts occur.

Mean marketable yields of organic and conventional pepper fruits per 1000 m² of cultivable area are respectively 2500 ± 500 kg and 4000 ± 1000 kg. Sales of organic pepper fruits are less sensitive than conventional pepper fruits to shape irregularity and surface imperfections, helping boost the organic cultivation marketable yield. In both cultivation systems, the field undergoes two mechanical agitations (by tractor-driven ploughing and harrowing) before manual planting of seedlings in rows of spacing between 50 – 70 cm. The final seedling spacing ranges from 35 – 45 cm.

Table 1

Table 1 follows Nemecek and Kagi (2007), and recreates ecoinvent's LCI dataset for Spanish irrigation water using the same production volume while fitting the ratio of groundwater to surface water and the electricity mix to the regional conditions. In both case studies, water is pumped from drilled wells of 60 m depth, using electric submersible pumps. When creating the Greek irrigation dataset, it is assumed that water is sourced solely from wells, and all energy supplied as electricity from the Greek energy grid, i.e. 54% lignite, 11% crude oil, 17% natural gas, and 18% renewable energy (Chatzisyneon et al., 2013). Drip irrigation is used in both systems.

After the seedlings have been planted, frequent light irrigation is employed, which becomes more intense as the plant mass increases. In general, organic cultivation achieves better water management and requires lower water inputs, because soils rich in organic matter retain water more efficiently (Bota and Benites, 2005; Kassam *et al.*, 2013). Estimation of irrigation water use is approximate, because such water use depends on soil type, rain frequency, climate, irrigation method and efficiency – the latter partly depending on individual farmers' environmental awareness. Our interviews indicate that organic farmers

1 are conscious of water saving and irrigation practices. Noting the local climate, where showers occur in
2 May and early June, we estimate that $\sim 400 \text{ m}^3/1000 \text{ m}^2$ and $\sim 360 \text{ m}^3/1000 \text{ m}^2$ of water are used for
3 conventional and organic open field pepper cultivation.

4 Organic cultivation partially covers its fertilizer requirements through crop rotation, residues, and
5 (primarily) through application of manure to the field before pepper seedlings are planted. The organic
6 farm under study uses potassium and calcium of organic nature and effective microorganisms (EM) as
7 fertilizers. Conventional pepper cultivation mainly utilizes chemical fertilizers derived from nitrogen,
8 phosphorus, and potassium (NPK). Table 1 lists the various system inputs, including chemical fertilizers,
9 herbicides, fungicides and insecticides employed in the conventional and organic farms.

10 Similar types of machinery are used in both systems. In organic pepper cultivation the field is firstly
11 ploughed, then harrowed, and afterwards manure is applied by mechanical means. During a single
12 cultivation period the field is tilled 5 times, essentially to remove unwanted vegetation. In conventional
13 pepper cultivation the field is in turn ploughed, harrowed, and has herbicides added to the soil. Fertilizing
14 is achieved after planting, by diluting fertilizers in water and feeding them to the plants by drip irrigation.
15 Spray applications of fungicides and insecticides to the field occur 3 to 5 times each, depending on hydro-
16 meteorological factors, such as rain frequency and temperature variation. A mean application rate of 4
17 times each is therefore assumed. Tillage is applied once, purely to improve soil aeration. The final stage
18 of cultivation involves harvesting of pepper fruits, which is performed manually and so does not affect the
19 relative environmental performance of conventional and organic systems. Harvesting is therefore left
20 outside the LCA boundaries.

21

22 **2.7 Impact assessment methodology**

23 Environmental performances of the two cultivation systems are compared at both midpoint and endpoint
24 levels using the ReCiPe impact assessment method, version 1.10 and SimaPro 8.0.1.4. Midpoint and
25 endpoint methods look at different stages in the cause-effect chain to calculate impact. The first examines
26 the impact earlier in the cause-effect chain, before the endpoint is reached, whereas the latter considers
27 environmental impact at the end of the cause-effect chain. The midpoint or problem-oriented approach
28 translates impacts into environmental themes, such as climate change and human toxicity, whereas the
29 endpoint or damage-oriented approach translates environmental impacts into issues of concern, such as
30 human health, natural environment, and natural resources. Endpoint results are associated with higher

1 levels of statistical uncertainty, compared to midpoint results, due to data gaps and assumptions stacking
2 up along the cause-effect chain, but are easier to understand by decision makers (PRé, 2014, 2016).

3 At midpoint level, ReCiPe uses the following 18 impact categories, which are given along with their
4 units: ‘climate change’ (CC), kg CO₂ to air; ‘ozone depletion’ (OD), kg chlorofluorocarbon (CFC-11) to
5 air; ‘terrestrial acidification’ (TA), kg SO₂ to air; ‘freshwater eutrophication’ (FE), kg P to freshwater;
6 ‘marine eutrophication’ (ME), kg N to freshwater; ‘human toxicity’ (HT), kg 1,4 dichlorobenzene
7 (14DCB) to urban air; ‘photochemical oxidant formation’ (POF), kg non-methane volatile organic carbon
8 compounds (MVOCs) to air; ‘particulate matter formation’ (PMF), kg PM₁₀ to air; ‘terrestrial ecotoxicity’
9 (TE), kg 14DCB to industrial soil; ‘freshwater ecotoxicity’ (FEC), kg 14-DCB to freshwater; ‘marine
10 ecotoxicity’ (MEC), kg 14DCB to marine water; ‘ionising radiation’ (IR), kg U²³⁵ to air; ‘agricultural
11 land occupation’ (ALO), m².yr of agricultural land; ‘urban land occupation’ (ULO), m².yr of urban land;
12 ‘natural land transformation’ (NLT), m² of natural land; ‘water depletion’ (WD), m³ of water; ‘metal
13 depletion’ (MD), Kg Fe; and ‘fossil depletion’ (FD), kg oil. At endpoint level these categories are
14 translated into 17 endpoint impact categories, which are then multiplied by damage factors and
15 aggregated into 3 endpoint damage categories. These are: ‘ecosystems’, ‘resources’ and ‘human health’,
16 the latter of which is partly expressed in terms of reduction in years of life expectancy and the number
17 of years living with a disability (called the Disability Adjusted Life Years (DALYs), an index that is also
18 used by the World Bank and World Health Organization (WHO)). The unit of ‘human health’ is years.
19 The ‘ecosystems’ damage category is expressed as loss of species over a specified area in a given
20 timespan, and its unit is years. The ‘resources’ damage category is expressed as the surplus cost of future
21 resource production over a finite timeframe (assuming constant annual production), considering a 3%
22 discount rate, and is given in units of 2000US\$ (PRé, 2014, 2016). These three endpoint damage
23 categories are normalized, weighted, and aggregated into a single score. Even though damage-oriented
24 (endpoint) methods are associated with high levels of uncertainty compared to problem-oriented
25 (midpoint) methods, the aggregation of results into a single score facilitates easier interpretation and
26 better communication to the public. A hierarchical (H) perspective is adopted, providing a consensus
27 model based on common policy principles regarding time-frame, etc. (PRé, 2014).

28 Two separate types of LCA are utilized in practice; namely, consequential (CLCA), and attributional
29 (ALCA). CLCA assesses the environmental consequences of a change in demand, such as how pollution
30 and resource flows within a system respond to a change in output of the functional unit. ALCA estimates

1 the environmental burden of a product (e.g. pollution and resource flows within a given system) attributed
2 to the delivery of a specified amount of the functional unit, assuming a status quo situation (Thomassen et
3 al. 2008). Given that the goal of the present work is to assess the environmental impacts of conventional
4 and organic pepper cultivation, which are largely unknown, we employ ALCA to identify emissions
5 associated with the life cycles of both systems.

6 Another important step in implementation of LCA is the sensitivity analysis, which is undertaken as a
7 systematic procedure to estimate the influence of the most significant parameters on the final outcome of
8 the study (Borklund 2002). Here, energy use is an important parameter, and so the diversification of
9 technologies used to compile the energy mix can have a decisive effect on the LCA results (Mathiesen et
10 al., 2009). For this reason, a sensitivity analysis has been performed using similar technologies for energy
11 production. The worst scenario comprises the use of lignite. Improvements include supplementing the
12 existing energy mix with other types of technologies based on renewable wind and solar energy sources,
13 which are abundant in Greece. Another important parameter is the yield of marketable pepper fruits,
14 because the different yields from the two systems can vary significantly. Thus, a further sensitivity
15 analysis was also performed to investigate the effect of changed assumptions regarding yields.

16 17 **3. Results and Discussion**

18 **3.1 Problem-oriented approach**

19 Results are expressed at midpoint level by means of a problem-oriented approach, which translates
20 impacts into the 18 environmental themes in order to identify key issues related to conventional and
21 organic pepper cultivation systems. Figure 2 shows the life cycle impact assessment (LCIA) results which
22 are expressed in units per tonne of marketable pepper fruit yield normalized using ReCiPe's European
23 reference inventories. For conventional pepper cultivation, the impact category with by far the highest
24 normalized score is 'freshwater eutrophication'. This especially high score, about 5 times higher than the
25 second highest category, 'marine ecotoxicity', is primarily attributed (78%) to the fertilizer stage, when
26 nitrogen and phosphorus from excess chemical fertilizer leach into groundwater or become transported
27 with sediment by runoff, polluting freshwater aquatic ecosystems, and promoting eutrophication
28 (Tuomisto *et al.*, 2012). Other impact categories that contribute to the environmental footprint of
29 conventional pepper cultivation, ordered from the highest to lowest scores, are: 'marine ecotoxicity';
30 'freshwater ecotoxicity'; 'human toxicity'; 'marine eutrophication'; 'natural land transformation'; and

1 'terrestrial acidification'. Except for 'marine eutrophication', these impact categories are most affected by
2 the irrigation stage, in particular the associated electricity consumption. 'Marine eutrophication' (nitrogen
3 enrichment of seawater) receives a lower score than 'freshwater eutrophication', reflecting the greater
4 resilience of oceanic ecosystems to direct nutrient emissions when fertilizers are applied in conventional
5 pepper cultivation. The use of pesticides mainly affects 'marine ecotoxicity', and to a lesser degree
6 'freshwater ecotoxicity' and 'human toxicity'. Although drip irrigation pipes have a minor impact on
7 'fossil depletion' due to their fabrication from PVC, their overall impact is very small owing to their
8 longevity.

9 For organic pepper cultivation (Figure 2), the midpoint impact category that has the highest score is again
10 'freshwater eutrophication'; in this case however, it has a normalized score of 0.253, which is about 3
11 times lower than that for conventional cultivation (with a score of 0.78). This confirms the direct
12 environmental impact of chemical fertilizers used in conventional agriculture, especially with regard to
13 freshwater eutrophication. Figure 2 also highlights that irrigation is overwhelmingly the main contributor
14 (~ 95%) to 'freshwater eutrophication', where organic cultivation is concerned. This is due to the
15 electricity consumed in pumping groundwater for irrigation. In Greece the energy mix is heavily
16 dependent on fossil fuels comprising 54% lignite, 11% crude oil, 17% natural gas, and 18% renewable
17 energy (Chatzisyneon *et al.*, 2013), and so emissions caused by fossil fuel extraction indirectly impact
18 the eco-system. More specifically, the impact on freshwater is due to phosphate emissions from lignite
19 mining and nitrogen oxides emissions from combustion (Atilgan and Azapagic, 2015). Irrigation is also
20 the main contributor to 'marine ecotoxicity', 'freshwater ecotoxicity', 'human toxicity', and 'natural land
21 transformation' impacts. Again, the primary cause is the fossil-dependent energy mix and its associated
22 direct and indirect emissions to the environment. Both lignite mining and combustion processes release
23 toxic materials including metals, sulphurs, and polycyclic aromatic hydrocarbons (PAHs) to the
24 environment, thus further contributing to the aforementioned adverse impacts (Stalikas *et al.*, 1997;
25 Atilgan and Azapagic, 2015). Machinery use also exhibits higher scores in all impact categories for
26 organic rather than conventional cultivation, owing to the more intense utilization of machinery in organic
27 agriculture. Moreover, manure transportation and spreading processes, absent in conventional cultivation,
28 lead to higher scores being attained for machinery processes because of the considerable quantity of
29 manure used in organic cultivation.

30 Figure 2

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3.2 Damage-oriented approach

The ReCiPe endpoint (damage-oriented) method is next applied. This method can translate environmental impacts into issues of concern or damage categories, namely human health, natural environment, and natural resources and thus is a very useful tool for researchers and policymakers. Figures 3 and 4 illustrate the main contributors to the total aggregated environmental impacts of conventional and organic pepper agriculture systems. For conventional cultivation, the main environmental impacts are attributed to irrigation (49.6%) and fertilizers (40.2%), with machinery contributing 10.2%. Irrigation impact is dominated by electricity consumption and agricultural machinery, which are responsible for 27.1% and 10.8% of the total environmental impact, respectively. The fertilizer impact is predominantly due to the use of nitrogen-phosphorus-potassium (N-P-K) compounds and calcium ammonium nitrate, which cause 30.5% and 5.22% of the total environmental impact. The high value attributed to N-P-K arises from (i) the direct adverse effects of N-P-K emissions to the environment including eutrophication, and (ii) the large quantities of energy and natural resources consumed in their production (Worrell and Blok, 1994).

Figure 3

For organic pepper cultivation, the key contributor to environmental impact is irrigation (68.5%) which consumes electricity (37.4%) from the Greek energy mix and relies on machinery (17.9%) including pumps and pipe networks for groundwater extraction (Figure 4). Machinery used for ploughing, harrowing, hoeing and manure application provides 23.5% of the total environmental impact. In organic cultivation, fertilizing is responsible for only 7.98% of the total environmental impact, which is mainly attributed to the transport of manure to the field.

Figure 4

Figure 5 presents the contributions at each stage (i.e. irrigation, fertilizing and machinery) to ReCiPe's 3 damage categories. Results are weighted to highlight the most important environmental impacts of each cultivation system. In both cultivation systems the 'human health' damage category yields the highest score. This damage category is the aggregated result of the following endpoint impact categories: 'climate

1 change human health'; 'ozone depletion'; 'human toxicity'; 'photochemical oxidant formation';
2 'particulate matter formation'; and 'ionizing radiation'. For conventional cultivation (Figure 6) the
3 'human health' damage category is primarily affected by irrigation (electricity consumption from the
4 Greek grid), secondarily by fertilizing (emissions originating from the underlying production processes),
5 and finally by machinery use (combustion of diesel fuel). For organic cultivation, irrigation is again the
6 main contributor to 'human health' damage, followed by machinery use, which is to be expected because
7 machinery is more intensively used in organic than in conventional cultivation. Finally, fertilizing only
8 makes a small contribution to this category, which is attributed to airborne emissions originating from
9 transport of manure to the field.

10 The second most affected damage category in both cultivation systems is 'resources'. This damage
11 category is a combination of ReCiPe's endpoint impact categories: 'metal depletion'; and 'fossil
12 depletion'. For conventional cultivation (Figure 6), the main areas of concern for 'resources' damage are
13 irrigation (again due to the energy mix) and fertilizing. In the latter case, the production of chemical
14 fertilizers consumes large quantities of natural resources and is also energy intensive, thus also providing
15 stress to the impact category on 'fossil depletion'. Machinery makes a small contribution, owing to the
16 burning of fossil fuels (diesel) during ploughing and harrowing, and to the metals used for machinery
17 construction. For organic cultivation, the 'resources' damage category is primarily affected by irrigation
18 (electricity from the Greek energy grid). Moreover, the greater use of machinery in organic cultivation
19 contributes to both metal and fossil depletion. Fertilizing makes the smallest contribution, which is
20 attributed to the diesel fuel burned during the transport of manure.

21 For both cultivation systems, the damage category with lowest score is 'ecosystems' which derives from
22 combining the following endpoint impact categories: 'climate change ecosystems'; 'terrestrial
23 acidification'; 'freshwater eutrophication'; 'terrestrial ecotoxicity'; 'freshwater ecotoxicity'; 'marine
24 ecotoxicity'; 'agricultural land occupation'; 'urban land occupation'; and 'natural land transformation'. In
25 conventional cultivation the main contributors include fertilizing (i.e. impacts on freshwater
26 eutrophication) and irrigation (i.e. indirect emissions from fossil fuels extraction and electricity
27 production). In organic cultivation the main contributor is irrigation, followed by machinery (i.e. indirect
28 emissions from machinery construction affecting mainly ecotoxicity impact categories).

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30 Figure 5

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2 By aggregating ReCiPe's three damage categories into a single score, the total environmental footprint is
3 estimated in terms of Eco-indicator Point (Pt) units, i.e. one thousandth of the yearly environmental load
4 of an average European citizen. Figure 6 indicates that both cultivation systems exhibit similar
5 environmental performance per product unit (1 tonne of marketable fruit yield). In particular, the
6 environmental footprint per tonne of conventional pepper cultivation is 11 Pt, slightly lower than that of
7 organic pepper cultivation, which is 11.5 Pt. Figure 6 shows that the damage category 'ecosystems'
8 attains a slightly lower score for organic cultivation than conventional agriculture. This lower score could
9 be attributed to the government ban on use of synthetic pesticides and nitrogen-based fertilisers, which
10 positively impacts on wildlife conservation and the landscape (Stolze *et al.*, 2000). Nonetheless,
11 conventional cultivation achieves lower scores in the 'resources' and 'human health' damage categories;
12 which may be attributed to the higher irrigation requirement and associated electricity consumption by
13 organic agriculture. Combustion of fossil fuels to produce electricity has a high impact on 'human
14 health'; this is particularly the case for lignite which is the main constituent of the Greek energy mix. The
15 'human health' damage category is also affected, to a lesser degree, by diesel consumption in the
16 machinery stage and by the manure spreading process that both result in airborne emissions. Organic
17 irrigation scores more highly for 'resources', again because of fossil-fuel usage by the irrigation system
18 and cultivation machinery. It should be noted that machinery makes a particularly high contribution to
19 'resources' damage because of the resources consumed during manufacture (e.g. metals, fossil fuels) and
20 operation (e.g. diesel consumption).

21 Therefore, even though conventional pepper cultivation strongly depends on chemical fertilizers, it
22 exhibits an overall slightly lower total environmental footprint, which is attributed to its higher (i.e. 4
23 tonne/yr) marketable fruit yield, compared to organic cultivation (2.5 tonne/yr). In other words, organic
24 cultivation requires more land, and hence more irrigation and machinery to hoe and plough the land, to
25 produce the same amount of pepper fruit product. Expressing the results per unit area of farmland, then
26 the environmental footprint of organic pepper cultivation is about 35 % lower than the conventional
27 system. This is in accordance with previous LCA studies comparing agricultural products from
28 conventional and organic farming systems, which have shown that impacts per area of farmed land are
29 usually lower in organic systems, but, when related to the quantity of products, the impacts often turn out
30 to be higher (Tuomisto *et al.*, 2012; Meier *et al.*, 2015; Foteinis and Chatzisyneon, 2016).

1 Potential limitations arise from the level of uncertainty of data collected during the LCI stage, data
2 availability, and the impact assessment methodology. First, the spatial scale is limited to Northern Greece
3 and its climate conditions. Moreover, the temporal scale of the collected data refers to 2015, when the
4 prevailing climate conditions were temperate, meaning that weather extremes lay outside the boundaries
5 of the study. Even though typical farms were examined, it is quite possible that a few farmers in the area
6 use non-typical types and quantities of pesticides/fertilizers and follow different cultivation practices, e.g.
7 surface irrigation, which could potentially lead to different environmental impacts. Nonetheless, the vast
8 majority of conventional and organic farmers are described by the data obtained from the farmers
9 surveyed, whilst typical climate conditions existed during the selected reference period, making results
10 robust. Another limitation is the absence of certain data from proprietary LCI databases. Data on
11 equivalent rather than exact machinery are used and only the main ingredients of pesticides are available
12 in existing databases.

13

14 Figure 6

15

16 **3.3. Sensitivity analyses**

17 A sensitivity analysis dealing with the marketable pepper fruit yield is carried out in order to investigate
18 the effect of changed assumptions regarding yields on the environmental sustainability of both cultivation
19 systems. In conventional agriculture the marketable pepper fruit yield ranges from 3 to 5 tons, whilst in
20 organic it ranges from 2 to 3 tons (Table 1). Worst-case and best-case scenarios are therefore examined
21 for each cultivation system, corresponding respectively to minimum and maximum marketable yields. For
22 the best-case scenario (maximum yield) the environmental impacts of both cultivation systems reduce
23 compared to the original scenario (mean yield). In the best-case scenario, the total environmental
24 footprint of conventional agriculture is 9.66 Pt, whereas that of organic is 10.84 Pt per tonne of
25 marketable pepper fruit. Thus, for highest yield, the conventional system has a total environmental
26 footprint per product unit about 11% lower than for the organic system. This is attributed to conventional
27 system having a higher maximum yield than the organic system. Both systems have similar
28 environmental footprints for the worst-case scenario of minimum marketable yield, with values of 16.09
29 (conventional) and 16.27 (organic) Pt per tonne of marketable pepper fruit. For the worst case-scenario,
30 both cultivation systems have increased environmental impacts compared to the original scenario (mean

1 yield). For both cultivation systems, the total environmental footprint is affected by marketable yield
2 changes, with conventional cultivation being more sensitive than organic. Weather has the greatest
3 influence on pepper yield, and so its influence is likely to be similar in both systems. However, pests
4 could restrict total marketable yield in organic cultivation, unlike conventional pepper systems where
5 pests are controlled by chemical means.

6 A second sensitivity analysis is carried out concerning electricity consumption during irrigation, one of
7 the main environmental hotspots experienced by both cultivation systems. Irrigation makes a high
8 contribution to the total environmental footprint of conventional and organic pepper cultivation systems.
9 First, irrigation relies on infrastructure and machinery for water withdrawal and transfer. Second,
10 irrigation consumes electricity for water pumping and distribution. In the present case studies, water is
11 directly withdrawn from wells; electricity driving the irrigation process is supplied by the Greek grid,
12 which is heavily dependent on fossil fuels and thus increases environmental impact. This effect is also
13 discernible in the total environmental footprint of organic pepper cultivation which is slightly higher than
14 conventional cultivation, because organic cultivation requires larger quantities of water per unit product.
15 Hence, the sensitivity of both cultivation systems is assessed with respect to the energy mix. For this
16 reason, best- and worst-case scenarios are employed and the response assessed of the conventional and
17 organic pepper cultivation systems. As a best-case scenario, an electricity mix totally comprising wind
18 and solar renewable energy sources (RES) is examined; both of these renewable energy sources are
19 readily available in Greece and could provide the electricity needed for water pumping. As a worst-case
20 scenario an electricity mix comprising lignite is considered; noting that lignite is amongst the least
21 environmentally-friendly choices. The original scenario is where electricity is provided by the existing
22 grid.

23 Scenario S1 entails use of wind energy for irrigation, instead of electricity imported from the Greek grid.
24 It is assumed that electricity generated by an onshore wind turbine (capacity in the range from 1 to 3
25 MW) could cover the energy needs of the irrigation process for both systems; the results are different to
26 those from the original scenario (i.e. electricity from the Greek grid). In Scenario S1, the total
27 environmental footprint of conventional cultivation reduces by about 26 %, to 8.09 Pt (c.f. 11 Pt in the
28 original scenario). For the 8.09 Pt case, irrigation, machinery, and fertilizing stages contribute 31.3 %,
29 13.9 %, and 54.8 % to the total environmental footprint. For the original scenario, electricity consumption
30 during irrigation contributes 2.99 Pt per tonne of conventional pepper yield or 27.1 % of the total

1 environmental footprint. In Scenario S1, electricity from wind energy results in a much lower value of
2 0.055 Pt per tonne of conventional pepper yield (i.e. 0.68 % of the total environmental footprint of
3 Scenario S1). The remaining 30.62 % or 2.475 Pt of the irrigation stage in Scenario S1 is attributed to
4 infrastructure and machinery required for irrigation, the values of which are similar for both organic and
5 conventional pepper cultivation.

6 The total environmental footprint for organic pepper cultivation amounts to 7.29 Pt per pepper fruit tonne,
7 achieving a 37 % reduction compared to the original scenario, where the total environmental footprint is
8 11.5 Pt. In Scenario S1, irrigation, machinery, and fertilizing stages are responsible for 50.2 %, 37.2 %
9 and 12.6 % of the total environmental footprint. Moreover, electricity from wind energy contributes only
10 1.09 % or 0.0792 Pt to the total environmental footprint, compared to 4.31 Pt or 37.4 % for the original
11 scenario. The remaining 49.1 % of the irrigation stage in Scenario S1 is again attributed to infrastructure
12 and machinery required for irrigation. Overall, the use of wind energy substantially reduces the predicted
13 total environmental footprint of conventional and organic pepper cultivation systems by 26 % and 37 %
14 respectively; the higher reduction of the organic system owing to its higher irrigation needs. As a result,
15 in Scenario S1 the organic system results in about 10 % lower total environmental footprint per product
16 unit, compared to conventional pepper cultivation. Moreover, when wind energy is used, organic pepper
17 cultivation yields a lower score in all three of ReCiPe's damage categories, compared to conventional
18 cultivation (Figure 7).

19 Scenario S2 examines use of solar energy. Figure 7 shows the results. In Scenario S2, photovoltaic (PV)
20 systems (3KWp single-Si panels mounted on slanted roofs) are used to provide electricity during
21 irrigation. The results are similar to those obtained for wind energy (Scenario S1). According to ReCiPe's
22 endpoint method, the total environmental footprint of conventional agriculture, when using solar energy,
23 is 8.27 Pt per pepper fruit tonne. In Scenario S2, irrigation contributes 32.8 %, machinery 13.7 % and
24 fertilizing 53.6 % to the total environmental footprint of conventional pepper cultivation. In this case,
25 electricity consumption during the irrigation stage amounts to 2.81 % (0.23 Pt) of the total environmental
26 footprint. This higher contribution reflects the fact that, in general, wind turbines have lower
27 environmental impact than solar PVs.

28 The environmental footprint of organic cultivation in Scenario S2 is 7.54 Pt, with irrigation, machinery,
29 and fertilizing responsible for 51.9 %, 35.9 %, and 12.2 % of the total environmental footprint. In this
30 case, electricity consumption from solar energy contributes 4.44 % (0.34 Pt) to the total environmental

1 footprint. Overall, use of solar energy again leads to substantial reductions in the total environmental
2 footprints of the conventional and organic pepper cultivation systems (by 25 % and 34 % respectively).
3 Therefore, in Scenario S2, organic cultivation exhibits 8.8 % lower environmental footprint per unit of
4 product, compared to conventional cultivation. For both solar and wind energy, organic pepper cultivation
5 yields a lower score in all three of ReCiPe's damage categories, compared to conventional cultivation
6 (Figure 7).
7 Finally, the worst-case Scenario (S3) is examined, where electricity originates solely from lignite
8 combustion. As expected, Scenario S3 exhibits the highest environmental footprint, and highest score in
9 all three damage categories considered (Figure 7). According to ReCiPe's endpoint method, the total
10 environmental footprint of conventional agriculture amounts to 12.07 Pt per pepper fruit tonne in
11 Scenario 3, of which 53.9 % is attributed to irrigation, 9.4 % to machinery use, and 36.7 % to fertilizing.
12 Electricity consumption during irrigation amounts to 33.4 % (~ 4 Pt) of the total environmental footprint,
13 reflecting the high environmental impact of lignite extraction and combustion as part of electricity
14 production. For organic cultivation, Scenario S3 yields a score of 13.01 Pt per pepper fruit tonne; with
15 irrigation, machinery, and fertilizing being responsible for 72.1 %, 20.8 %, and 7.1 % of the total
16 environmental footprint. Electricity consumption originating from lignite contributes by 44.6% (5.8 Pt) to
17 the total environmental footprint. As a result, conventional cultivation in Scenario S3 exhibits ~ 7 %
18 lower environmental footprint per unit of product, compared to organic cultivation. For both cultivation
19 systems the use of lignite led to a higher score in all three of ReCiPe's damage categories, compared to
20 the foregoing scenarios (Figure 7). Overall, the use of lignite increases the environmental impact of both
21 systems, highlighting the importance of the electricity mix composition on the total environmental
22 sustainability of agricultural cultivation systems.

23

24 Figure 7

25 **4. Conclusions**

26 The environmental footprint and key environmental hotspots of organic and conventional open field
27 pepper cultivation systems have been identified by LCA methodology using information from a case
28 study in the Anthemountas basin (Northern Greece). The main conclusions are listed below:

- 29 • At midpoint level, the highest normalized environmental impact of both cultivation systems is in
30 the 'freshwater eutrophication' damage category. Owing to direct emissions from the much

1 greater use of chemical fertilizers, conventional cultivation attains a score three times larger than
2 organic cultivation.

- 3 • At endpoint level, irrigation provides the major impact for both cultivation systems, mainly due
4 to the high consumption of electricity supplied from the Greek energy mix. It should be noted
5 that the Greek mix is dominated by fossil fuels (i.e. 54% lignite, 11% crude oil, 17% natural gas,
6 and 18% renewable energy) and therefore yields high environmental impact.
- 7 • Overall, both cultivation systems have similar total environmental impacts. Organic cultivation
8 achieves a slightly lower score for the ‘ecosystems’ damage category, whereas conventional
9 cultivation performs better in the ‘resources’ and ‘human health’ damage categories. In total,
10 conventional cultivation exhibits a slightly better environmental performance due to its higher
11 crop yield and to Greece’s fossil-fuel-dependent electricity mix used during the irrigation stage.
12 If results are expressed per unit of area, then organic pepper cultivation has about 35 % lower
13 total environmental impacts in the resources, ecosystems, and human health damage categories.
- 14 • When wind and solar energy are used to meet the electricity needs of the irrigation stage, both
15 systems have decreased environmental footprint. Organic agriculture has a lower total
16 environmental footprint (about 10% and 9% in the case of wind and solar energy, respectively)
17 and also a lower score in all three damage categories (i.e. ‘ecosystems’, ‘resources’ and ‘human
18 health’) compared to conventional agriculture. In short, the introduction of renewable energy
19 sources (RES) is likely to improve the sustainability of conventional and organic pepper
20 cultivation systems, especially the latter. On the other hand, if a fossil fuel oriented energy mix
21 such as lignite is introduced, then both systems will exhibit higher environmental impact, with
22 organic cultivation being affected the most due to its higher water inputs per unit of product.

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