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Environmental impacts of urban hydroponics in Europe: a case study in Lyon

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Abstract

The food provisioning of European cities depends on the global food supply system. However, both economic crises, environmental pressure and climate change effects represent a risk for food chain stability. Urban agriculture (UA) increases the self-sufficiency and resiliency of cities and is able to deliver positive environmental and social benefits. However, its efficacy depends on several variables, including the type of UA and the geographical location of the city. This paper analyses ReFarmers' pilot farm, a vertical high-yield hydroponic croft located in the urban area of Lyon, France, from a life cycle perspective. The results show that the hydroponic farm performs better than cultivations in heated greenhouses, and similarly to conventional open field farms. Moreover, the source of the electricity input is a determinant factor that, if carbon neutral (e.g. wind energy) allows vertical hydroponic production to outperform the two conventional types of agriculture.

Keywords: Life Cycle Assessment; Urban agriculture; Hydroponics

1. Introduction

The urban population in Europe has been growing at a constant rate in the last 50 years, and is expected to reach 80% of the total European population by 2050 [1]. This represents a challenge for food provisioning, since cities are not able to internally satisfy it [2]. Hence, the import of goods is necessary to meet the food demand of urban citizens, which has caused an increased dependency on the global food production and supply system. Such a reliance on external inputs represents a vulnerability when major political or economic disruptions occur, and it can often be the leading cause of such instabilities [3, 4]. The inequality in food distribution represents an additional risk, worsen by the increasing urban poverty [5, 6].

Adding on to the local challenges for food provisioning, the global food supply chain is also vulnerable to big-scale changes. In fact, climate change will put food security at risk on several levels, for example by reducing yields and land suitability, and by increasing frequency and severity of extreme weather events [7]. Satisfying the demand of fertilisers is another environmental challenge of food production, given that mineral fertilisers are a non-renewable resource that is being consumed at an increasing rate [8].

In addition to being vulnerable to disruptions, the food system is also responsible of environmental degradation [9]; considering the environmental impacts generated by the final consumptions of the European Union, the production and distribution of foodstuff accounts for 30% of the impacts on climate change, 33% of the impacts on ecotoxicity and 60% of the impacts on eutrophication [10].

Urban agriculture (UA) has been proposed as a practice to respond to the challenges presented above, and produce positive environmental, economic and social effects, such as shortening the food supply chain, reducing the emissions of greenhouse gasses, microclimate improvement, improved water management, improved diet-related health, and stress reduction[3, 11–15]. Smit and Nasr [16] pointed out that urban

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agriculture could promote the development of a circular economy by closing ecological loops using wastewater and organic solid waste as inputs. However, urban agriculture is not a homogeneous practice, and includes, among the others, small commercial farms, community-supported agriculture, community gardens, rooftop gardens or greenhouses, hydroponic and aquaponics farms and indoor agriculture [17]. Mougeot [18] proposed to categorize UA based on types of economic activity, products, location, area used, production system, production scale, and product destination. Given this variability, a case-by-case evaluation is needed to show if and in what conditions UA can deliver positive impacts and can replace conventional agriculture.

Urban agriculture has been studied from a life cycle perspective, reporting different results that show that UA is not a less impacting production system per se. For example, Kulak et al. [14] calculated that up to 34 t CO_{2eq} ha^{-1} a^{-1} could be avoided by substituting conventional agricultural products with vegetables from community gardens in the UK. On the other hand, for Goldstein et al. [19] urban agriculture in northern climates performs worse than its conventional counterpart, mainly because of its high energy requirement and/or low yields. Sanyé-Mengual et al. [20] evaluated a rooftop greenhouse production in Barcelona: their results show that the UA system had a lower impact on the environment, but that crop efficiency was determinant for the performance of the cultivation.

This case study analyses, from an environmental perspective, a vertical hydroponic urban farm called "La Petite Ferme du Grand Lyon" and based in Lyon (France), using Life Cycle Assessment. The pilot farm is run by the private company ReFarmers and produces leafy greens and herbs that are sold directly to restaurants and citizens.

2. Methods

Life Cycle Assessment (LCA) is a methodology used for the evaluation of the environmental impacts of a product or a service. Its utility in the food sector has been recognized, thanks also to the opportunity of improving the performance of a product by acting on the most burdensome processes [21].

2.1. Goal and scope definition

This work's goal is to evaluate the environmental performance of a high-yield vertical hydroponic farm, and to compare it to conventional agriculture. The analysis shows whether and to what extent this type of hydroponic is able to produce vegetables with a lower environmental impact than soil-based conventional agriculture. By showing if urban agriculture can compete with conventional vegetable production, this study highlights the strong and weak points of urban hydroponic production in temperate continental climates, and therefore supports the improvement and development of sustainable urban food supply systems.

Urban agriculture is, in this case, a supplementary source of vegetables; therefore, the capacity of urban hydroponic agriculture to fulfil the entire food requirement of European cities is outside of the scope of this study.

The modelling framework applied is attributional LCA. According to the ILCD Handbook we identified our case study as a Situation A "micro-level, product or process-related decision support study". In fact, by having a small market share, the farm's products can impact on the market solely to a limited extent, generating only small-scale consequences [22].

2.1.1 Functional unit

The selected functional unit is one kg of leafy greens delivered to the retailer. To be able to perform the comparison between hydroponic and conventional agriculture, we assumed that: lettuce and leafy greens can be considered substitutes, given their almost overlapping function; the quality of the vegetables is the same for all cultivation types. The same assumptions were made and described by Goldstein et al. [19].

2.1.2 System boundaries

We performed a cradle-to-gate analysis considering the cultivation phase and the transport of the products to the retailers. Figure 1 shows the boundaries of the system. Capital goods were included into the analysis as they are considered fundamental assets in hydroponic cultivation. The end-of-life of the capital goods was selected depending on the material: steel, aluminium and iron parts are recycled, as well as PVC and PE plastic components; the other plastic materials, which cannot be recycled due to their composition, are sent to incineration.

We had to exclude the process of pest control through insect release; the insects are not bred in the farm, and no literature data could be found about the breeding process of parasitoids and the related inputs. The fixation of CO_2 by the plants was omitted because the gas is expected to be released in the near future as a biogenic emission of carbon dioxide. Moreover, as we compare the same amount of produced lettuce, the uptake of carbon dioxide is the same for both types of cultivation. Since the fertilisers are not lost through the soil, but remain available to the plants thanks to the recirculation of the water, we assumed the fertilisers emissions to be zero.

For conventional agriculture, we considered two scenarios: the production and delivery of lettuce grown in heated greenhouses (scenario S2) and the production and delivery of open field cultivated lettuce (scenario S3); both the scenarios were derived from the Ecoinvent database [23].

In all the three scenarios, the packaging of the vegetables has not been included. This choice is justified by the fact that the impact of packaging has been showed to be relatively low [24].

2.1.3 Impact categories

The impact assessment was performed using the software Simapro 8 and the ReCiPe methodology (version 1.13) at Midpoint level. We focused on seven impact categories that, accordingly to Goldstein et al. [19], are considered representative of the main potential impacts of agriculture: climate change (CC), freshwater and marine eutrophication (respectively FE and ME), freshwater ecotoxicity (FT), agricultural land occupation (ALO), water depletion (WD) and fossil depletion (FD).

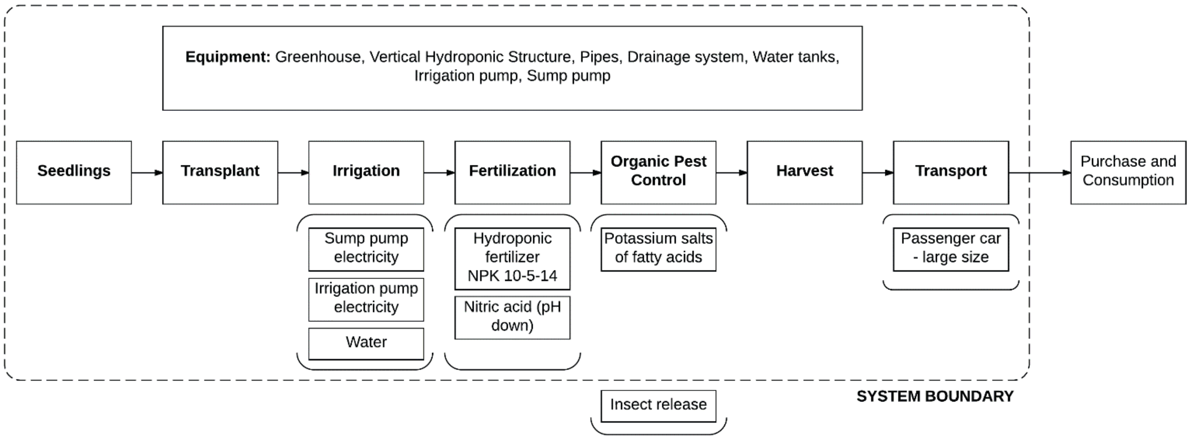

Figure 1. System boundaries.

2.1.4 Sensitivity analysis

Based on the results of the Life Cycle Impact Assessment (LCIA), we performed a one-at-a-time (OAT) analysis of scenario S1; the parameters that contributed most to the impacts were varied of ±10%, and the change in the results was calculated and discussed.

A scenario sensitivity analysis was also carried out for scenarios S1 and S2: the type of one of the most impacting inputs was changed to see the performance of the scenarios in these new conditions.

3. Results and discussion

3.1. Life Cycle Inventory

The Life Cycle Inventory (LCI) of scenario S1 (Table 1) consists of data provided by the farmers, covering four months of production in 2016. The annual production was extrapolated considering the seasonal variation of some inputs, such as the water demand. Moreover, we took into account that the production stopped for 1.5 months in winter due to low temperatures. The losses of production in the farm are indirectly accounted for, since the farmers reported the yields as production ready to be sold, i.e. the losses has been already subtracted.

The farm covers an area of around 325 m^2, of which (at the time of the analysis) only 18% were used for the plant cultivation. The seedlings are not produced in the farm but bought from a local organic company; since no direct data were available, we refer to the seedling production process from Stössel et al. [24]. We assumed no heating is required, since the plant variety are selected according to the season.

A neighbour farm manages the transport to the retailers of the vegetables from the hydroponic farm, together with their production; a mass allocation was performed to distribute the impacts of this process, and a car trip of 20 km per week was estimated. No losses of products are assumed in this phase, due to the length and frequency of the trip.

The Ecoinvent database was the source of the inventories of scenarios 2 and 3. In particular, we referred to the market activity dataset "market for lettuce, GLO, Allocation, at the point of substitution, ecoinvent database version 3.3", and to the ordinary datasets "Stössel F., lettuce360 production, GLO (Global), Allocation, at the point of substitution, ecoinvent database version 3.3", and "Stössel F., lettuce361 production, GLO (Global), Allocation, at the point of substitution, ecoinvent database version 3.3".

Table 1. Life Cycle Inventory of scenario S1.

Output	U/M	Value	Lifetime
Leafy greens (lettuce)	kg	1	
Inputs	U/M	Value	Years
Polyester greenhouse	kg	$4.34*10^{-5}$	15
Iron greenhouse	kg	$3.01*10^{-5}$	50
Aluminium greenhouse	kg	$3.29*10^{-4}$	50
Steel greenhouse	kg	$2.53*10^{-3}$	50
PVC greenhouse	kg	$1.23*10^{-4}$	50
Polyethylene greenhouse	kg	$6.39*10^{-4}$	15
Polycarbonate greenhouse	kg	$5.71*10^{-4}$	15
PVC structure	kg	$8.87*10^{-3}$	20
Recycled PET matrix media	kg	$7.04*10^{-3}$	5
Polyester rope	kg	$2.83*10^{-4}$	6
Steel hanging hook	kg	$4.96*10^{-5}$	50
PVC gutter	kg	$2.61*10^{-3}$	50
PVC pipe	kg	$1.27*10^{-4}$	50
PE tubing	kg	$2.16*10^{-4}$	25
Steel tubing	kg	$1.02*10^{-3}$	50
HDPE tank1	kg	$2.31*10^{-4}$	25
Steel tank1	kg	$2.76*10^{-4}$	25
HDPE tank2	kg	$1.34*10^{-4}$	25
Irrigation pump	n	$3.73*10^{-5}$	10
Sump pump	n	$3.73*10^{-5}$	10
Organic seedlings	n	1.96	
Peat for seedlings	cm^3	39.1	
N in fertiliser	kg	$2.57*10^{-2}$	
P_2O_5 in fertiliser	kg	$1.29*10^{-3}$	
K_2O in fertiliser	kg	$3.60*10^{-3}$	
Nitric acid	L	$5*10^{-3}$	
Potassium hydroxide pest	kg	$7.97*10^{-5}$	
Coconut oil pest control	kg	$7.97*10^{-5}$	
Water pest control	kg	$1.85*10^{-2}$	
Electricity irrigation pump	kWh	2.29	
Electricity sump pump	kWh	0.15	
Water irrigation	L	5.96	
Urban land use	m^2a	$2.24*10^{-2}$	
Transport	t*km	$1.00*10^{-2}$	

Table 2 reports the yields and the water and fertiliser inputs required by the three scenarios. In scenario S1, five cultivation cycles can be achieved per year, while scenarios S2 and S3 support four cycles per year.

Table 2. Comparison of yield, water and fertiliser consumption of the three types of cultivation.

	S1	S2	S3
Yield [kg/m^{2}year]	44.7	20.0	10.4
Water consumption [L/kg]	5.96	42.3	23.2
Fertiliser use per kg of product [kg/kg]:			
N	0.0026	0.0016	0.0037
P as P_2O_5	0.0013	0.0005	0.0007
K as K_2O	0.0036	0.0024	0.0052

3.2. Life Cycle Impact Assessment

Table 3 reports the results of the Life Cycle Impact Assessment for the four scenarios.

As an overview, the urban vertical hydroponic production (S1) shows the best performance in the categories of marine eutrophication and agricultural land occupation. For climate change, freshwater eutrophication, freshwater ecotoxicity and fossil depletion, the impact is higher than on-field conventional agriculture (S3). Anyway, in all cases except for water depletion the performance of S1 is visibly better than the production of lettuce in heated greenhouses (S2).

These results are explained by taking into consideration the characteristics of the different systems. The vertical hydroponic farm requires more capital goods than the other types of cultivations, since it does not rely on soil substrate, but needs vertical plastic structures and a recirculating irrigation system, which requires electricity (see Figure 2).

For climate change, the consumption of electricity contributes for two thirds to the impact in scenario S1, while in scenario S3 the production and use of fertilisers are the main responsible of greenhouse gas (GHG) emissions. Whereas these two scenarios differ for only 0.10 kg CO_{2eq}, when lettuce is grown in heated greenhouses (scenario S2), it is responsible of the emission of 7.08 kg CO_{2eq} per every kg of lettuce that reaches the supermarket.

By recirculating water and avoiding losses for infiltration, scenario S1 has a water consumption seven times lower than greenhouse conventional production, and around four times lower than on-field cultivation, that benefits from rain events (see Table 2). In Mediterranean climates, such as Greece, the water demand per kg of lettuce production reaches 83 litres, fourteen times higher than in vertical hydroponics [25]. However, the irrigation system requires a constant water flow guaranteed by a pumping system, which consumes electricity. The impact of electricity depends on how this electricity is produced; given the location of the farm, we considered the French energy mix, of which more than 70% is nuclear energy [26]. The production of nuclear energy has a high requirement of cooling-water, which explains why scenario S1 has a worse impact on water depletion, even if it has a smaller direct water consumption.

Table 3. Results of the Life Cycle Impact Assessment of 1 kg of lettuce grown in the three scenarios: vertical hydroponic production (S1), heated greenhouse production (S2) and on-field cultivation (S3). The results are normalised with respect to the yields in Table 2.

Impact category	S1	S2	S3
CC [kg CO_{2eq}]	0.39	7.1	0.29
FE [kg P_{eq}]	$5.88*10^{-5}$	$3.10*10^{-4}$	$1.27*10^{-5}$
ME [kg N_{eq}]	$1.14*10^{-4}$	$8.91*10^{-4}$	$1.37*10^{-3}$
FT [kg 1,4-DB_{eq}]	$2.55*10^{-4}$	$9.98*10^{-4}$	$1.69*10^{-4}$
ALO [m^2a]	0.024	0.522	0.095
WD [m^3]	0.033	0.019	0.017
FD [kg oil_{eq}]	0.10	1.43	0.07

The consumption of electricity for irrigation is among the main contributing processes for all the impact categories, but is less impacting than the consumption of heat of the conventional greenhouse scenario. In facts, scenario S2 has the worst performance (except for water depletion) in every category.

The controlled temperature in S2 results in a doubled yield with respect to on-field cultivation, but still half of the one of vertical hydroponic (see Table 2). Having a high production in a limited space is one of the main qualities of vertical hydroponic systems. Moreover, since no soil is needed, the cultivation can take place in many different spaces: on rooftops, indoor, on abandoned industrial sites, on walls. An additional positive characteristic of hydroponics is that the quality and eventual contamination of the soil does not represent a risk for the products – simply because the two compartments are not in direct contact. This advantage is shown in the agricultural land occupation of scenario S1: by being soil independent and vertical, this type of hydroponics requires from four to 20 times less agricultural land than conventional agriculture.

However, this means that hydroponic production needs to be supported by an external input of fertilisers to satisfy the nutrient requirement of the plants. The use of NPK fertiliser in the three scenarios is reported in Table 2. Scenario S1 needs more nutrient input than greenhouse cultivation, but less than on-field production, where part of the applied fertilisers is lost due to leaching processes. The different NPK proportion indicates that hydroponics allows an optimization of nutrient supply to support the growth phases of the plants.

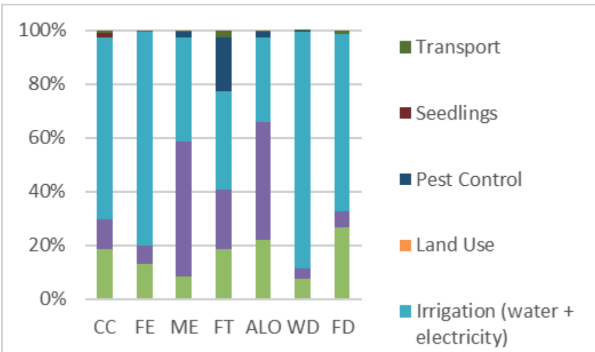

Figure 2. Process contribution of scenario S1 in the seven impact categories

These results do not completely explain the impacts on freshwater eutrophication: in scenarios S1 the production of electricity and fertilisers are the main contributing processes, and in scenario S2 the production of heat is the dominant process. Scenario S3 has a negligible use of these inputs, but needs more fertilisers, which determines the emission of nutrients into the water streams. It is important to distinguish where the emissions of nutrients take place, since eutrophication is a local phenomenon. In this sense, in scenario S1 and S2 the major risk of eutrophication is in the areas where fuels, metals and fertilisers are extracted, i.e. mining sites distant from the place of final use. On the contrary, in scenario S3 the release of nutrients following the application of fertilisers represents a noteworthy impact on local water quality.

About marine eutrophication, the actors in play are the same of freshwater eutrophication (electricity, fertiliser production and use), but since scenario S3 has a high release of nitrogen (which is the limiting factor of ME), its impact is higher than scenario S1.

Regarding eutrophication, a merit of hydroponics is the efficient use of nutrients, that, by being recycled with the water, are not released through the soil but remain available for the plants. The impact on freshwater ecotoxicity is due to the heat consumption in scenario S2, whereas for the other two scenarios several processes impact with the same order of magnitude: electricity production, fertiliser production, equipment production, pesticide production and transport.

The combination of equipment and energy requirements is responsible of the impact of scenario S1 on fossil depletion. Scenario S2, due to the necessity to heat the greenhouse, has a performance more than ten times worse, while on-field cultivation (S3), that is relatively low-input, has half the impact of S1.

A benefit of urban agriculture is the shortening of the supply chain and the reduction of losses during the transport of the products. Thanks to the proximity of the farm to the consumers, the vegetables are fresher and do not need to be cooled during the delivery. For these reasons, we assumed zero losses in the transport phase. For conventional agriculture, on the other hand, the reported distribution losses are approximately 12%.

3.2.1 Sensitivity analysis

To determine the influence of the main inputs identified in the LCIA, we performed a one-at-a-time (OAT) analysis of scenario S1 by varying the yield, the electricity consumption and the water consumption by ± 10%. The results in Table 4 show that the yield is the parameter that most affects the results, especially when it changes negatively. Variations in electricity consumption have different effects on the different categories, but notably this parameter is more important than water for the water depletion impact category.

We performed also a scenario sensitivity analysis where we considered the case in which the hydroponic farm (S1) and the heated-greenhouse farm (S2) use only wind energy to satisfy their energy requirements. We chose this type of energy because wind is the second renewable energy source in France, after hydropower, and is easier to implement than the latter [26].

Table 4. OAT sensitivity analysis.

Impact category	Yield +10%	Yield -10%	Electricity ±10%	Water ±10%
CC [kg CO_{2eq}]	-9.1%	+11.1%	±6.7%	±0.1%
FE [kg P_{eq}]	-9.1%	+11.1%	±7.9%	±0.0%
ME [kg N_{eq}]	-9.1%	+11.1%	±3.9%	±0.0%
FT [kg 1,4-DB_{eq}]	-9.1%	+11.1%	±3.7%	±0.0%
ALO [m^2a]	-9.1%	+11.1%	±3.1%	±0.1%
WD [m^3]	-9.1%	+11.1%	±7.0%	±1.8%
FD [kg oil_{eq}]	-9.1%	+11.1%	±6.5%	±0.1%

As visualized in Table 5, the use of wind energy makes the hydroponic production the least impacting method of cultivation, except for the impacts on freshwater where it is comparable to on-field agriculture. The use of wind energy in the heated greenhouse improves the overall performance of this scenario, however, this cultivation remains the one with the highest impacts on the considered categories.

Table 5. Scenario sensitivity analysis: LCIA of scenario S1 using wind energy as electricity input.

Impact category	S1 wind energy	S2 wind energy
CC [kg CO_{2eq}]	0.156	1.139
FE [kg P_{eq}]	$1.61*10^{-5}$	$6.60*10^{-5}$
ME [kg N_{eq}]	$7.86*10^{-5}$	$6.72*10^{-4}$
FT [kg 1,4-DB_{eq}]	$1.74*10^{-4}$	$2.98*10^{-4}$
ALO [m^2a]	0.0017	0.071
WD [m^3]	0.011	0.018
FD [kg oil_{eq}]	0.044	0.252

3.2.2 Data quality and limitations of the study

The quality of the data influences the results. The primary data collected for scenario S1 refer to four months of production. Even if the farmers considered the seasonal variability for a better estimation of the annual consumptions, e.g. the water consumption, we recognise that the annual estimations could eventually not correspond to the actual values.

Moreover, scenarios S2 and S3 are based on LCI datasets representative of the Integrated Production in Switzerland. Even though the authors of the datasets affirm that, most probably, their data are representative for similar cultivations in industrialised countries, these values cannot capture the peculiarities of country-specific cultivation practices. In conclusion, we acknowledge that the data do not have the same level of precision, and this affects the quality of the results.

To compare the performance of the systems, we chose the environmental indicators considered the most representative for LCA analyses of agricultural systems. We recognise that the agricultural sector can deliver other positive and negative effects, such as potential contribution to biodiversity, social issues and economic development. Consequently, integrating the analysis with other methodologies could give a broader perspective on the impacts of agriculture on an environmental, economic and social level.

4. Conclusions

The results of the comparative analysis of lettuce production in vertical hydroponic, heated greenhouse and on-field cultivation show that the former is able to deliver higher yields and have an environmental impact comparable to on-field cultivation, and 2 to 12 times lower than heated greenhouse production. A special case is represented by the impact on water depletion, where the type of energy used affects the results more than the direct water consumption. In conclusion, the need of energy inputs is determinant for the efficiency of plant production systems, as highlighted by the bad performance of scenario S2, due to the need for heating. When the needs of external inputs are satisfied using fossil-based resources, the environmental performance decreases, but if renewable sources are used, the high yields and efficiency make vertical hydroponic the best production system in the considered climatic area. Moreover, the ability to grow local food without agricultural land occupation is for sure an added value of vertical hydroponics, representing a less environmentally harmful way to supplement the vegetable demand of urban populations.

Acknowledgements

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