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Environmental and economic assessment of multiple cultivation techniques and crops in open-air community rooftop farming in Bologna (Italy)

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Abstract.

Background: Urban rooftop farming (URF) is sprouting around cities thereby integrating agriculture in available urban spaces and enhancing local food production. Besides, different crops and cultivation systems can be used in URF. Quantitative environmental and economic information of these systems may support the design of future URF projects.

Experimental: Life Cycle Assessment and Life Cycle Costing were used to quantify the environmental burdens and economic costs of an open-air community rooftop garden. For leafy vegetables (lettuce), three cultivation types were compared: Nutrient Film Technique (NFT), floating hydroponic and substrate cultivation. Five different fruit vegetables (tomato, chili pepper, eggplant, melon, watermelon) were grown in substrate production. Experimental trials were realized between 2012 and 2014 in the rooftop garden of a public housing building in Bologna (Italy).

Results: For leafy vegetables, most environmentally-friendly options were the floating technique in summer crops (65-85% lower) and substrate production in winter (85-95% lower), while in substrate production, eggplants and tomatoes were the fruit vegetables that showed best environmental performances (≈74 g $CO_2 \cdot kg^{-1}$). From the economic point of view, floating production was 25% cheaper in summer and substrate was 65% cheaper than NFT production of lettuce, while substrate production of eggplants resulted in the cheapest crop (0.13 €$\cdot kg^{-1}$). We here demonstrate that URF production is an environmentally-friendly option for further develop urban local production. We recommend that community URF designs include re-used elements and promote horticultural knowledge to improve their sustainability performance.

Keywords: urban agriculture; local food; building-integrated agriculture; rooftop farming; life cycle assessment; agronomy; hydroponics

1. INTRODUCTION

Urban Rooftop Farming (URF) is sprouting around cities driven by the growing interest in urban agriculture (Mok et al. 2013). URF is growing in popularity in such a way that urban planning policy has started to include it, such as in New York City. Rooftops have become a new resource thereby providing spaces for food cultivation in highly populated cities (Cerón-Palma et al. 2012; Specht et al. 2014; Thomaier et al. 2015). Among URF types, open rooftop farming is the most common (Thomaier et al. 2015) in contrast to more complex systems, such as rooftop greenhouses, which need a higher economic investment, or indoor farming, linked to a large energy demand.

Open-air rooftop farming experiences are found worldwide and range from educational to commercial projects. "Food from the sky" is a community food project that takes advantage of the empty rooftop of a supermarket in North London (United Kingdom) with the aim of increasing the community food security. In the Trent University (Toronto, Canada), an educational rooftop garden is managed by students to produce food for the local campus restaurant. The rooftop gardens in various Fairmont Royal Hotels in Canada supply the kitchen demand with own-cultivated herbs, tomatoes, peas, beans and berries in beds and pots. The Eagle Street rooftop farm and the Brooklyn Grange are the most well-known rooftop farms of New York (USA), which combine local food production with education and social programs.

Research on these forms of urban agriculture has mainly focused on theoretical and agronomic aspects. Thomaier et al. (2014) reviewed current URF projects and discussed their contribution to a sustainable urban agriculture. Cerón-Palma et al. (2012) and Specht et al. (2014) provided a compilation of barriers and opportunities of URF based on focus group discussions and available literature, respectively. Whittinghill et al. (2013) and Orsini et al. (2014) have performed agronomic studies of rooftop gardens to account for their productivity and their variability (e.g., different cultivation systems, seasonality) in Michigan (United States) and Bologna (Italy), respectively.

Notwithstanding the sustainable image of URF, only a few studies have focused on the quantification of their environmental, economic and social impacts. Astee and Kishnani (2010) analyzed the potential domestic vegetable production of rooftop farming in Singapore and the resulting CO_2 savings by reduced food imports. In the same line, Sanyé-Mengual et al. (2015a) evaluated the potential RTG implementation in industrial parks in Barcelona through a GIS-LCA guide, which includes a self-sufficiency and environmental assessment of local production. Sanyé-Mengual et al. (2013) quantified the environmental benefits of the local supply-chain of tomatoes produced in rooftop greenhouses (RTGs) in Barcelona (Spain) and contrasted with the conventional supply-chain of tomatoes from Almeria (Spain). Sanyé-Mengual et al. (2015b) accounted for the environmental burdens of the structure of an RTG and compared it to a conventional greenhouse, since more resources are consumed for reinforcing

RTGs to meet legal requirements of buildings' technical codes. However, the environmental and economic impacts of food production in open-air URF systems have not yet been studied. Furthermore, community URF experiences differ from other commercial systems (eg., RTGs) as they provide further social services (e.g., social inclusion), are managed by amateurs and are usually low-cost designs.

Besides, multiple cultivation systems can be used in URF (FAO, 2013). Current projects involve from sophisticated growing systems (e.g., high-tech hydroponics) to soil-based crops cultivated in recycled containers (e.g. pallet cultivation). Among them, soil-based is the most commonly used technique (Thomaier et al. 2015). Even more, some rooftop farming experiences combine agriculture production with livestock, such as "The FARM:shop" in London (United Kingdom) which provides vegetables, fish and chicken products through an integrated rooftop-aquaponic system (Local action on Food 2012). Some studies have dealt with the efficiency of different cultivation techniques from an agronomic perspective. Pennisi (2014) compared the crop yield of producing lettuce in rooftop farming through NFT (Nutrient Film Technique), floating and substrate (i.e., mix of perlite, coconut fiber and clay) systems. At the city level, Grewal and Grewal (2012) quantified the potential production of urban agriculture, differentiating within cultivation scenarios, from conventional to hydroponic production, thereby highlighting the different efficiency and food supply capacity of them. In this sense, the quantification of the environmental burdens and economic costs of different cultivation systems for open-air farming may support the design decision-making process.

The general aim of the paper is to assess urban rooftop farming from an environmental and economic point of view. The objectives of the study are to quantify both the environmental impacts and economic costs of a real case study by applying the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methods. Specific objectives are, first, comparing three different cultivation techniques (NFT, floating, substrate) for leafy vegetables production (lettuce); second, accounting for the burdens of substrate production of multiple fruit vegetables (tomato, melon, watermelon, chili pepper and eggplant); and, finally, assessing the sensitivity of the results to the availability of re-used materials and the use intensity of the rooftop garden. A community rooftop farming in the city of Bologna is analyzed for this purpose.

2. MATERIALS AND METHODS

The paper analyses the outputs of experimental crops performed in Bologna (Italy) by following the LCA (ISO 2006) and the LCC (ISO 2008) methods for accounting for the environmental burdens and the economic cost of the systems.

2.1. Experimental crops

Experimental trials were performed from April 2012 to January 2014 in the rooftop of a public housing building in the city of Bologna (Italy). Bologna is a representative case study of Mediterranean cities, where climatic conditions are favorable for year-round open-air rooftop farming practices. The experimental crops were performed in a community garden implemented on the 250 m^2 terrace of the 10^{th} floor of the building. Three different cultivation systems were used in the trials: modified NFT, floating and substrate (illustrated in Fig. 1). The modified NFT (Fig. 1a) was done on re-used PVC pipes, where leafy vegetables were placed in net pots to be in contact with the nutrient solution, which was recirculated and supported with additional irrigation. The floating system (Fig. 1b) consisted of a wooden container (made of re-used pallets and waterproofed with a plastic film), filled with the nutrient solution that was oxygenated with an aerator, where plants were grown on net-pots placed on a floating polystyrene board. Substrate production (Fig. 1c) was also done on wooden containers where plants were grown on commercial soil with compost and fertilizers. Tap water was used for irrigation in all the systems since rainwater harvesting (RWH) system were not considered in the design. Trials were performed for six crops including leafy and fruit vegetables: lettuce (*Lactuca sativa* L.), tomato (*Solanum lycopersicum* L.), melon (*Cucumis melo* L.), watermelon (*Citrollus lanatus* Thumb.), chili pepper (*Capsicum annuum* L.) and eggplant (*Solanum melongena* L.) (Fig. 1). Leafy vegetables were cultivated in NFT, floating and substrate, while fruit vegetables were only grown in substrate. Crop cycles are indicated in Fig. 1 as Days-After-Transplanting (DAT) values. Other vegetables although not included in this analysis, were grown year-round in the garden. In particular, chicory and black cabbage were initially considered for assessing leafy vegetables production although were finally excluded due to low crop yield values.

2.2. Life Cycle Assessment

This section describes the goal and scope, Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) steps followed in both LCA and LCC analysis.

2.2.1. Goal and scope

Crop production is assessed from a cradle-to-farm gate approach by including the following life cycle stages: cultivation system (i.e., the life cycle impact of cultivation elements), auxiliary equipment (i.e., irrigation system), crop inputs (i.e., substrate, energy, water and fertilizers) and waste management. The analysis is performed for each individual crop (i.e., lettuce, tomato, melon, watermelon, chili pepper and eggplant) and the functional unit is 1 kg of product.

2.2.2. Life Cycle Inventory (LCI)

Tab. 1 compiles the life cycle inventory of the three cultivation systems under assessment: NFT, floating and substrate systems. LCI data for the assessment is divided into cultivation system, auxiliary equipment, and crop inputs. Cost data is shown in terms of unitary costs and per year of use.

(a) Cultivation systems and auxiliary equipment

The cultivation systems included in the analysis are modified NFT in PVC pipes, floating in wood container and substrate in wood container (Fig. 1). Type and amount of materials are obtained from the experimental trials in Bologna and the designs detailed in Marchetti et al. (2012). Wood containers are made of re-used pallets while former PVC pipes are used in the NFT system. When materials are re-used, the environmental impacts of their extraction and manufacturing are excluded from the assessment as they belong to the former product. The auxiliary equipment includes all the elements related to the irrigation system required for each crop. Pumps and timer materials are excluded from the system boundaries due to the low repercussion per functional unit, based on a mass cut-off criterion. LCI data is compiled in Tab. 1. LCI background data for materials extraction, processing, transportation and electricity generation are obtained from ecoinvent 2.2. database (Swiss Center for Life Cycle Inventories 2010). Since the cultivation systems are used year-round for multiple crops, their impact is allocated for each crop product according to their crop cycle (indicated as Days-After-Transplanting values in Figure 1).

(b) Crop inputs

Crop inputs depend on cultivation system and crop. First, water consumption is determined by cultivation system, crop, plant density and crop cycle. For substrate cultivation, irrigation is of 11.7 $L \cdot m^{-2} \cdot d^{-1}$ for tomato and lettuce, 4.7 $L \cdot m^{-2} \cdot d^{-1}$ for eggplant, 7.2 $L \cdot m^{-2} \cdot d^{-1}$ for chili pepper, 2.6 $L \cdot m^{-2} \cdot d^{-1}$ for melon and 3.7 $L \cdot m^{-2} \cdot d^{-1}$ for watermelon. For NFT, crops are irrigated with the nutrient solution through a recirculation system at a rate of 1.9 $L \cdot m^{-2} \cdot d^{-1}$ in autumn-winter cycles and of 3.9 $L \cdot m^{-2} \cdot d^{-1}$ in summer cycles. For floating cultivation, the container is filled with the nutrient solution and losses per evapotranspiration are replaced, resulting into a consumption of 1.3 $L \cdot m^{-2} \cdot d^{-1}$ in autumn-winter cycles and of 4 $L \cdot m^{-2} \cdot d^{-1}$ in summer cycles. Energy consumption includes the requirements for the irrigation timer, the recirculation pump (i.e., NFT) and the aerator (i.e., floating).

Fertilizers are supplied in a solid form in substrate cultivation and as a nutrient solution in NFT and floating. For substrate, 30 $g \cdot m^{-2} \cdot y^{-1}$ of N-P-K 15-5-20 with 2 $g \cdot m^{-2} \cdot y^{-1}$ of MgO and micronutrients are yearly supplied. For NFT and floating, the nutrient solution contains the following fertilizers: NPK (80 $mg \cdot L^{-1}$), $CaNO_3$ (30 $mg \cdot L^{-1}$) and KNO_3 (40 $mg \cdot L^{-1}$). Substrate cultivation is done on potting soil, where compost is added to regenerate it and to complete fertilization at a rate of 210 g·m^{-2} of soil. Compost is made by the rooftop garden users by composting the biowaste from crops and their own organic waste. Plants in NFT and floating systems are placed on net pots with a mix of substrates: perlite (1/3), coconut fiber (1/3) and expanded clay (1/3). All crops are pesticide-free.

LCI data is obtained from the experimental trials, detailed in Orsini et al. (2014) and Marchetti (2012). LCI data for home composting of green biowaste is obtained from Colón et al. (2010). Background data for the LCI is completed from the ecoinvent 2.2. database (Swiss Center for Life Cycle Inventories 2010) and the LCA Food database (Nielsen et al. 2003).

(c) Waste management

Waste management includes only the management of the elements of the cultivation materials at their end of life, since biomass is reintroduced in the crop cycle through composting. Cultivation materials (i.e., from cultivation system and auxiliary equipment) are 100% recyclable. As a result, their treatment is excluded from the analysis and only their transportation is considered (recycling plants are located 30 km away from the site).

(d) Cost data

Costs of the different materials and elements of the cultivation systems and auxiliary equipment are obtained from suppliers, as well as for substrate and fertilizers. Tap water cost is 0.00153 €·L^{-1}, according to Bologna's supplier (Gruppo Hera). Electricity cost is 0.1539 €·kWh^{-1} (EUROSTAT 2014). Transportation cost is 0.003 €·kgkm^{-1}, according to the transport type, consumption rate and current fuel prices. Material costs of re-used elements are considered as 0, although the related transportation and construction requirements are accounted for.

2.2.3. Sensitivity assessment

Two variables are assessed as sensitivity parameters: the availability of re-used elements and the use intensity of the rooftop garden. First, although the current design is made of re-used materials, they can be also made with new pallets and pipes (e.g., lack of re-used pallets sources), particularly when re-used elements are unavailable. Thus, a "Raw materials scenario" shows the potential increase in the resources consumption, considering that cultivation systems are made of new elements (i.e., raw materials) and multiple crops are done during the entire year (i.e., environmental impacts and costs of the cultivation system are allocated to the different crop periods).

Second, community and private gardens can be used seasonally, leading to a low use intensity (e.g., only summer crops), or can be year-round thereby combining autumn-winter and spring-summer crop cycles. A "Low use intensity scenario" assumes that only one crop is done during the entire year and, therefore, the environmental impacts and costs of the cultivation system of the entire year are allocated to one crop.

2.2.4. Life Cycle Impact Assessment (LCIA)

The environmental impact assessment is performed by applying the LCIA stage. The SimaPro 7.3.3 software (PRé Consultants 2011) is used to conduct the LCIA, which follows classification and characterisation steps determined as mandatory by the ISO 14044 regulation (ISO 2006). The LCIA is carried out at the midpoint level, and methods applied are the ReCiPe (Goedkoop et al. 2009) and cumulative energy demand (CED) (Hischier et al. 2010). With respect to the ReCiPe, the hierarchical time perspective is considered, as recommended in the ILCD Handbook (EC-JRC 2010). The environmental indicators include the global warming (GW, kg CO_2 eq), the water depletion (WD, m^3) and the cumulative energy demand (CED, MJ). Besides, the human toxicity potential (HT, kg 1.4-DB eq.) is used to evaluate potential effects on human health. The LCC assessment considers the cost of the systems and results are shown through the total cost (TC, €) indicator.

3. RESULTS AND DISCUSSION

The environmental impacts and economic costs of crop production in open-air rooftop farming are shown and discussed in this section. First, the three cultivation techniques under assessment (substrate, NFT, floating) are compared for the production of leafy vegetables. Second, the environmental performance and costs of substrate production for multiple vegetables are discussed. Finally, the sensitivity of the results to the availability of re-used materials and the use intensity of the garden is assessed.

Table 2 compiles the environmental and economic results for the production of fruit and leafy vegetables in the rooftop garden. Substrate production of eggplant and tomato obtained the lowest environmental impact in global warming (0.073 kg $CO_2eq \cdot kg^{-1}$), human toxicity (0.027 kg 1-4DBeq$\cdot kg^{-1}$) and energy consumption (1.20 $MJ \cdot kg^{-1}$), while eggplant was the cheapest crop (0.17 €$\cdot kg^{-1}$). Lettuce production in floating technique was the most water efficient production (<0.04 $m^3 \cdot kg^{-1}$). On the contrary, lettuce production in NFT was the most expensive (1.47 €$\cdot kg^{-1}$, on average) and the most impacting crop in global warming (3.78 kg $CO_2eq \cdot kg^{-1}$, on average), human toxicity (0.84 kg 1-4DBeq$\cdot kg^{-1}$, on average) and energy consumption (57.1 $MJ \cdot kg^{-1}$, on average), because of the large energy consumption of the recirculation pump and the low crop yield (1.3 $kg \cdot m^{-2}$, on average). Finally, lettuce production in substrate consumed the largest amount of water (0.39 $m^3 \cdot kg^{-1}$) since substrate production is the least water efficient system and crop yield was low (1.5 $kg \cdot m^{-2}$). When correlating these results with the agronomic data, relation to crop yield and crop period were moderately significant (R^2>0.6). The lower the crop yield and the longer the crop period, the higher the environmental impacts and costs.

From the economic perspective, prices ranged between 0.13 and 1.95 €·kg^{-1} and irrigation was the most contributing stage. Overall production costs of some crops (e.g., NFT and floating lettuce production) resulted larger than current market prices because of two main issues. First, given the importance of water consumption, urban gardeners pay a higher value for water since drinkable water is more expensive than water in rural agrarian areas. Second, one may consider that community rooftop farming provides further services than the food production itself. Thus, social services such as hobby, community building or education may be included in the cost-benefit assessment by accounting for the economic value of these positive externalities.

3.1. Comparing cultivation techniques for leafy vegetables

Figure 2 compares the environmental impacts and economic costs of lettuce production in NFT, floating and substrate. Results depended on the season. In summer cycles, floating production of lettuce showed the lowest environmental burdens and economic costs. In winter cycles, substrate production was the most environmentally-friendly and cheapest option, although floating production was the most water-efficient one.

For lettuce production in summer, floating production had an environmental impact per kg around 75% lower and costs were 25% cheaper than NFT. Causes of this divergence are the lower crop yield in NFT (46% lower), the longer crop period (almost 2 times, on average), the electricity consumed by the recirculation pump and the higher water consumption in the NFT system.

For lettuce production in winter, substrate was the more environmentally-friendly and cheaper option, apart from the water depletion indicator where the floating technique consumed the lowest amount per kg ($0.04m^3 \cdot kg^{-1}$). Electricity consumption for irrigation purposes was the lowest in substrate production (i.e., timer), compared to the other systems where the use of electric devices is more intensive (i.e., recirculation pump, aerator). However, water consumption in substrate production was 10 times larger because of a longer crop cycle, a lower crop yield ($1\ kg \cdot m^{-2}$, the lowest of the three techniques) and larger irrigation requirements per kg of product. In particular, substrate production of leafy vegetables became a water inefficient system, since the irrigation rate ($1.3L \cdot day^{-1} \cdot plant^{-1}$) was the same as for some fruit vegetables (e.g., tomato). Thus, leafy vegetables were irrigated at a fruit vegetable rate although their water requirements are lower. This is caused by the simultaneous production of multiple vegetables, while in a monoculture design water requirements would be crop-specific.

As a result, NFT is the worst option from both an environmental and economic perspective. Furthermore, notwithstanding the feasibility of using NFT crops in Bologna area, the use of this technique in the Mediterranean climate is limited to moderate temperatures. Major temperature changes can be produced in warmer areas (south Mediterranean) due to the low volume of nutrient solution, leading to a higher risk of plant mortality (FAO 2013).

For all the cultivation techniques, 'crop inputs' was the most contributing life cycle stage to the different environmental indicators (>85%). In NFT production, 70% of the environmental impact was associated with the electricity consumed during irrigation, in particular for the recirculation of the nutrient solution. In floating production, the irrigation (nutrient solution and electricity) was responsible for 60% of the impact. In substrate production, water accounted for the 75% of the overall impact. Furthermore, auxiliary equipment related to the irrigation system (e.g., timer, pump) made this life cycle stage the second most expensive one. Thus, improvements in the design of cultivation systems for leafy vegetables may focus on the irrigation requirements and the associated elements.

3.2. Substrate production of fruit vegetables

Figure 3 displays the environmental impact and economic cost of substrate production of fruit vegetables. These crops had a global warming impact ranging from 68 to 194 g of CO_2 eq., a human toxicity impact between 0.02 and 0.7 kg 1-4DB eq, a water depletion between 50 to 158 L, and an energy consumption between 1.14 a 3.05 MJ. Total costs per kg varied from 0.17€ to 0.44€, being the crop inputs the major cost (52%, on average) (Tab. 2). The life cycle stage that contributed the most to the environmental indicators turned out to be the irrigation (≈ 70%), particularly in water depletion where it accounted for almost the 100%. Within the irrigation system, the consumption of tap water was the main contributor to the water depletion (≈ 52%) and economic cost (≈ 80%), while the electricity consumed by the pump and the timer was the main cause (45-65%) of the other environmental indicators.

Among fruit vegetables, the production of tomatoes and eggplants were the cheapest and most environmentally-friendly crops. This trend is related to the high yield of these crops (8.2 $kg \cdot m^{-2}$ for eggplant and 13-14 $kg \cdot m^{-2}$ for tomatoes), compared to the other crops with productivities lower than 5 $kg \cdot m^{-2}$. On the other hand, chili pepper and melon were the crops that obtained the highest impact values, depending on the indicator (Table 2).

Since irrigation was the most contributing element, the use of rainwater harvesting systems may reduce the environmental impact. The substitution of the current tap water consumption with collected rainwater could reduce the global warming impact by between 12 and 60%, depending on the crop. When the amount of rainwater collected satisfies the whole crop water demand, water depletion could be avoided (i.e., become 0). Although there is available space in the rooftop garden for introducing rain-collecting systems, the main constrain is actually given by the weight load of these reservoirs, which were not considered when the building was designed. On the other hand, if rainwater would be stored at ground level, supplementary energy to pump it to the 10^{th} floor may be considered in the environmental and economic balance. However, for newly implemented buildings with integrated rooftop gardens, these constrains may be easily overtaken.

3.3. Cultivation systems design: sensitivity assessment of availability of re-used materials and use intensity of the garden

The sensitivity to the availability of re-used materials and the use intensity of the garden was analyzed. Primarily, environmental impacts and economic costs of crop production in cultivation systems built with new elements (i.e., new pallets and new PVC pipes) were compared with the case study (i.e., re-used pallets and pipes). The environmental impact of a "raw materials scenarios" was from 1.1 (NFT) to 1.8 (substrate) folds higher than the reference scenario. The most sensitive indicator was the CED, which rose up to 3 times in substrate production (data not shown).

The availability of re-usable elements in urban areas may be a limiting factor for the design of sustainable rooftop farming systems. In this case study, pallets and PVC pipes are the re-usable elements. First, pallets are growing in popularity due to their suitability for designing household elements, such as furniture, and garden elements. To date, the used pallets market is growing and availability seems guaranteed due to the worldwide use of these elements in the logistics sector. On the other hand, re-usable PVC pipes are less available for citizens, although the integration of these elements in a growing market of re-used elements may become way to manage the end-of-life of the current tap water distribution network. Moreover, PVC pipes have the lower global warming impact of the most common pipes used in urban water distribution networks (Sanjuan-Delmás et al. 2014).

Results of the year-round production systems (Table 2) were also compared to crop production in cultivation systems where only one crop is done per year (i.e., seasonal use). A "low use intensity scenario" showed an increase in the environmental impact of between 1.2 (NFT) and 2 (floating) folds (data not shown). Again, CED resulted to be the most sensitive indicator. Consistently, the impact associated with rooftop gardening can be highly affected by its use intensity. As a matter of fact, educational and training programs from public entities (e.g., municipality, associations and educational centers) are therein crucial in enabling citizens' knowledge on horticultural systems and their appropriate management. Skills on horticulture, crop production and crop planning may enhance the sustainability of community rooftop farming by leading to a year-round production (e.g., diversification of crops and crop cycles).

For lettuce (multiple crop cycles), the sensitivity to use intensity and availability of re-used materials was related to crop yield and crop period values. On NFT, the variation in the environmental impact of lettuce production was strictly related to the crop yield ($R^2 > 0.99$). The higher the crop yield, the lower the variation in the environmental indicators. On the contrary, the sensitivity to the availability of re-used elements for the design depended on the crop period ($R^2 \approx 0.8$). The shorter the crop period, the lower the increase in the environmental indicators when using new materials. The same trends were found for lettuce production in floating technique.

4. CONCLUSIONS

The paper accounted for the environmental impacts and economic costs of crop production in a community rooftop farming in Bologna, thereby contributing to the sustainability assessment of urban agriculture from a quantitative approach. The environmental impacts and economic costs of the crops strongly depended on cultivation technique, crop yield and crop period. Substrate production of eggplants and tomatoes, which had the highest crop yields, showed the best environmental and economic performance, except for water consumption where lettuce production in floating technique was the most efficient option. For leafy vegetables, floating technique and substrate production were the best options, depending on the indicator and season.

As a community-managed system, the home-made compost and pesticides-free production allowed decreasing the chemicals consumption in substrate crops. Furthermore, the crop diversity of the community garden positively contributed to supply the food demand of the residents and use the garden year-round. Finally, the knowledge and training of rooftop garden users can affect the environmental and economic indicators, depending on their crop management efficiency and the final outputs of the rooftop farming.

Compared to other types of urban rooftop farming, the case study showed better environmental and economic performances than rooftop greenhouses. For instance, tomatoes produced in the open-air rooftop garden in Bologna had a global warming impact 3 times lower and economic cost 3.5 times lower than tomatoes produced in a Rooftop Greenhouse in Barcelona, from a cradle-to-farm gate approach (Sanyé-Mengual et al. 2015). Thus, rooftop gardens can become a key way to promote urban agriculture in residential areas, where the investment in high-tech infrastructures (e.g., greenhouses, aquaponics) is more unlikely. Even more, residents can obtain cheap and environmentally-friendly products that can boost the food security of urban areas (Orsini et al. 2014) and, in particular, can benefit certain marginal areas and stakeholders groups with little access to healthy food.

Notwithstanding the potential benefits of open-air rooftop farming, the design of the cultivation system and the crop planning are crucial points to optimize the environmental and economic performance of these systems. Rooftop farming design may focus on the potential local resources that can be used in the construction stage, particularly on those elements that can have a second life in the garden through re-use (e.g., pallets, pipes, wheels). Moreover, the design may include different type of cultivation systems. This is because fruit and leafy vegetables have different requirements. According to the results, we would recommend the use of substrate techniques for fruit vegetables and winter cycles of leafy vegetables, while floating production would be interesting for summer crops of leafy vegetables. On the contrary, NFT would be the least recommended option. Regarding management, crop planning may focus on selecting the vegetables (e.g., combination of fruit vegetables with higher crop yield and leafy vegetables) and establishing crop periods to diversify the production during spring-summer and fall-winter cycles, thereby producing year-round and reducing the environmental impacts and economic costs of crops. Further research may focus on applying social indicators in URF future studies or integrate social services as positive externalities in the overall economic balance.

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TABLE CAPTIONS

Table 1. Life cycle inventory data of the cultivation systems and crop inputs for substrate, modified NFT and floating, for 1 m^2 and a lifespan of 1 year. Crop inputs are defined per year, crop or day, depending on cultivation systems. Water and electricity consumption for irrigations is shown per day since crop cycles are different and water demand depends on crop.

Table 2. Environmental and economic indicators for lettuce crops (substrate, NFT and floating) and substrate production. Results correspond to the functional unit of 1 kg of product per crop period. Indicators are Global Warming (GW, kg CO_2 eq), Water depletion (WD, m^3), Cumulative Energy Demand (CED, MJ), Human Toxicity (HT, kg 1,4-DB eq.) and Total cost (TC, €).

FIGURE CAPTIONS

Figure 1. The experiment considered three different cultivation types for leafy vegetables: floating in wooden containers (1a), modified NFT in PVC pipes (1b) and substrate in wooden containers (1c) (Modified from Orsini et al. 2014). Experiments were performed between 2012 and 2014 (2). The six crops followed different cycles: spring-summer, summer, autumn or autumn-winter (2).

Figure 2. Environmental and economic burdens of substrate, NFT and floating production for leafy vegetables: lettuce. The indicators used are Global Warming (GW, kg CO_2 eq), Water depletion (WD, m^3), Cumulative Energy Demand (CED, MJ), Human Toxicity (HT, kg 1,4-DB eq.) and Total cost (TC, €).

Figure 3. Environmental and economic burdens of substrate production for leafy and fruit vegetables. The indicators used are Global Warming (GW, kg CO_2 eq), Water depletion (WD, m^3), Cumulative Energy Demand (CED, MJ), Human Toxicity (HT, kg 1,4-DB eq.) and Total cost (TC, €).

Table 1. Life cycle inventory data of the cultivation systems and crop inputs for modified NFT, floating and substrate, for 1 m^2 and a lifespan of 1 year. Crop inputs are defined per year, crop or day, depending on cultivation systems. Water and electricity consumption for irrigations is shown per day since crop cycles are different and water demand depends on crop.

	Element	Material	Unit	Cultivation systems			Unitary cost	
				NFT	Floating	Substrate		
Cultivation system	Pallet	Wood	kg	-	3.34	3.34	0	€·kg^{-1}
	Screws	Steel	kg	-	0.007	0.007	23.8	€·kg^{-1}
	Angle iron	Iron	kg	-	0.052	0.052	11.5	€·kg^{-1}
	Wood agent	Varnish	L	-	0.02	0.02	0.81	€·L^{-1}
	Pipes	Polyvinylchloride (PVC)	kg	1.62	-	-	0	€·kg^{-1}
	PS board	Polystyrene (PS)	kg	-	0.27	-	0.096	€·kg^{-1}
	Construction	Electricity	kWh	-	0.009	0.009	0.1539	€·kWh^{-1}
	Transport	Van, 3.5t	kgkm	4.7	21.5	20.8	0.003	€·kgkm^{-1}
Auxiliary equipment	Sticks for support	Bamboo	kg	-	-	0.18	0	€·kg^{-1}
	Net pot	PVC	g	25	46	-	0.074	€·g^{-1}
	Water tank	PVC	g	223.5	-	-	0.012	€·g^{-1}
	Irrigation tubes	Polyethylene (PE)	g	56.6	-	12	0.004	€·g^{-1}
	Drippers	Polypropylene (PP)	g	2.8	-	11.1	0.17	€·g^{-1}
	Microtubes	PVC	g	2.3	-	3.6	0.04	€·g^{-1}
	Supporting stakes	PP	g	6.8	-	2.7	0.03	€·g^{-1}
	Barbed connectors	PP	g	2.3	-	0.9	0.15	€·g^{-1}
	Transport	Van, 3.5t	kgkm	2.6	0.23	1.22	0.003	€·kgkm^{-1}
	Timer	-	-	1/8.5	-	1/36	2.70	€
	Aerator pump	-	-	-	1/1.2	-	6.62	€
	Recirculation pump	-	-	1/8.5	-	-	3.47	€
Crop inputs	Water	Tap water	L·d^{-1}	-	-	2.6-11.7	0.00153	€·L^{-1}
	Electricity	Timer/Pump	kWh·d^{-1}	0.0624	0.019	0.0033	0.1539	€·kWh^{-1}
	Fertilizers	Compost	g·y^{-1}	-	-	210	0	€·g^{-1}
		NPK 15-5-20	g·y^{-1}	-	-	30	0.001	€·g^{-1}
	Fertirrigation	Nutrient solution	L·d^{-1}	1.96-3.92	1.3-4	-	0.003	€·L^{-1}
	Substrate	Commercial soil	kg·y^{-1}	-	-	2.09	0.045	€·kg^{-1}
		Perlite	kg·crop^{-1}	0.27	0.49	-	0.493	€·kg^{-1}
		Coir	kg·crop^{-1}	0.27	0.49	-	0.453	€·kg^{-1}
		Clay	kg·crop^{-1}	0.27	0.49	-	0.267	€·kg^{-1}
	Transport	Van, 3.5t	kgkm	29.19	51.10	12.75	0.003	€·kgkm^{-1}
Waste management	Transport	Van, 3.5t	kgkm	58.2	111.37	108.31	0.003	€·kgkm^{-1}

Table 2. Environmental and economic indicators for modified NFT, floating and substrate production. Results correspond to the functional unit of 1 kg of product per crop period. Indicators are Global Warming (GW, kg CO_2 eq), Water depletion (WD, m^3), Cumulative Energy Demand (CED, MJ), Human Toxicity (HT, kg 1,4-DB eq.) and Total cost (TC, €).

	GW [kg CO_2 eq,]	HT [kg 1-4DB eq,]	WD [m^3]	CED [MJ]	TC [€]
NFT					
Lettuce-2012	2.51	0.542	0.0911	38.1	1.09
Lettuce-2013(1)	4.88	1.09	0.196	73.3	1.36
Lettuce-2013(2)	3.97	0.889	0.0855	60.5	1.95
FLOATING					
Lettuce-2012	0.567	0.109	0.0395	9.37	0.67
Lettuce-2013(1)	1.19	0.234	0.0904	19.6	1.42
Lettuce-2013(2)	1.08	0.231	0.0393	18.6	1.29
SUBSTRATE					
Chili pepper	0.174	0.06.10	0.158	2.80	0.35
Eggplant	0.0766	0.02.41	0.0501	1.21	0.13
Lettuce-2013(2)	0.323	0.123	0.389	5.15	0.74
Melon	0.194	0.0553	0.0788	3.05	0.28
Tomato-2012	0.0753	0.0308	0.0980	1.26	0.18
Tomato-2013	0.0679	0.0277	0.0881	1.14	0.16
Watermelon	0.133	0.0399	0.0719	2.09	0.21

Figure 1:

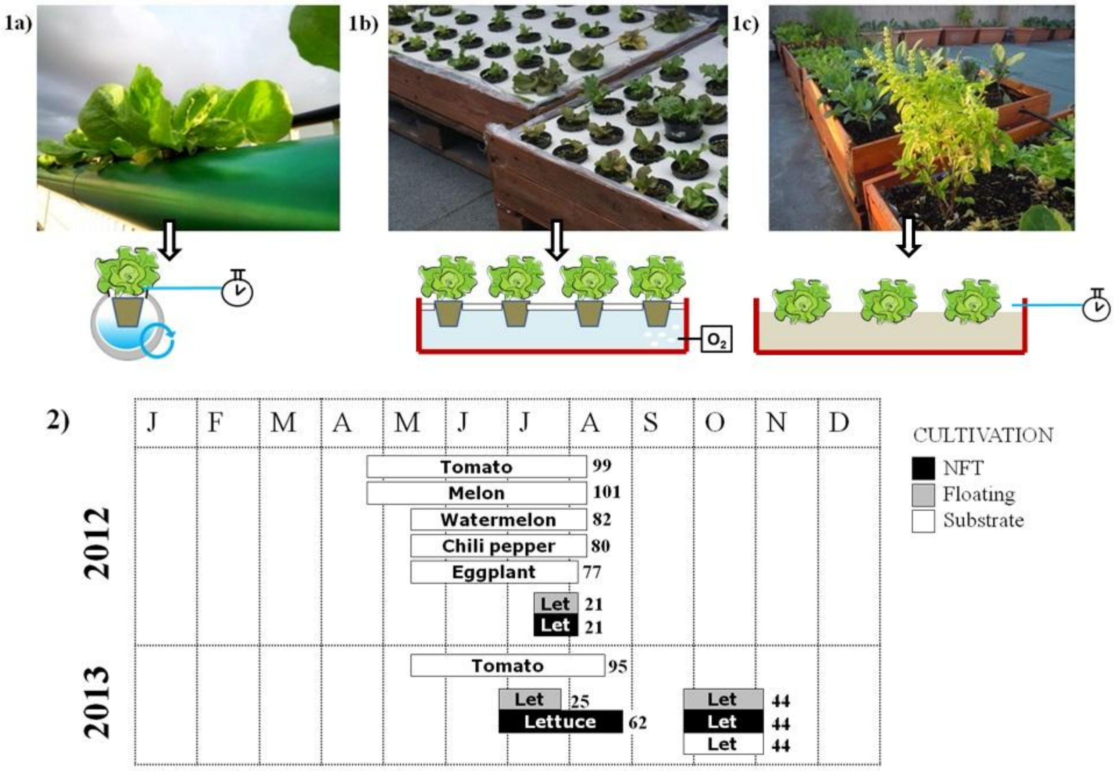


Figure 2:

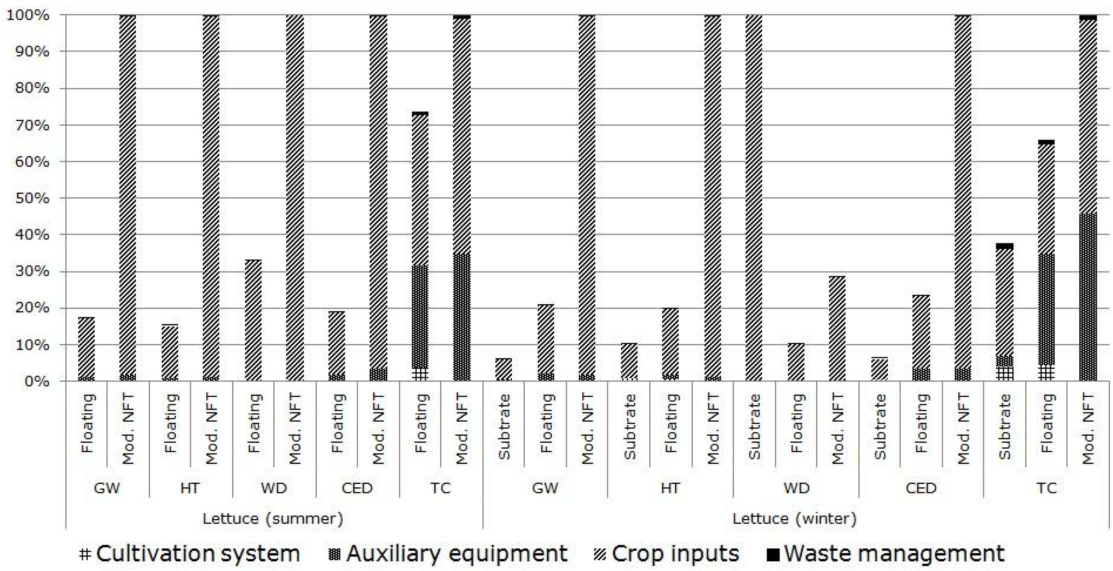
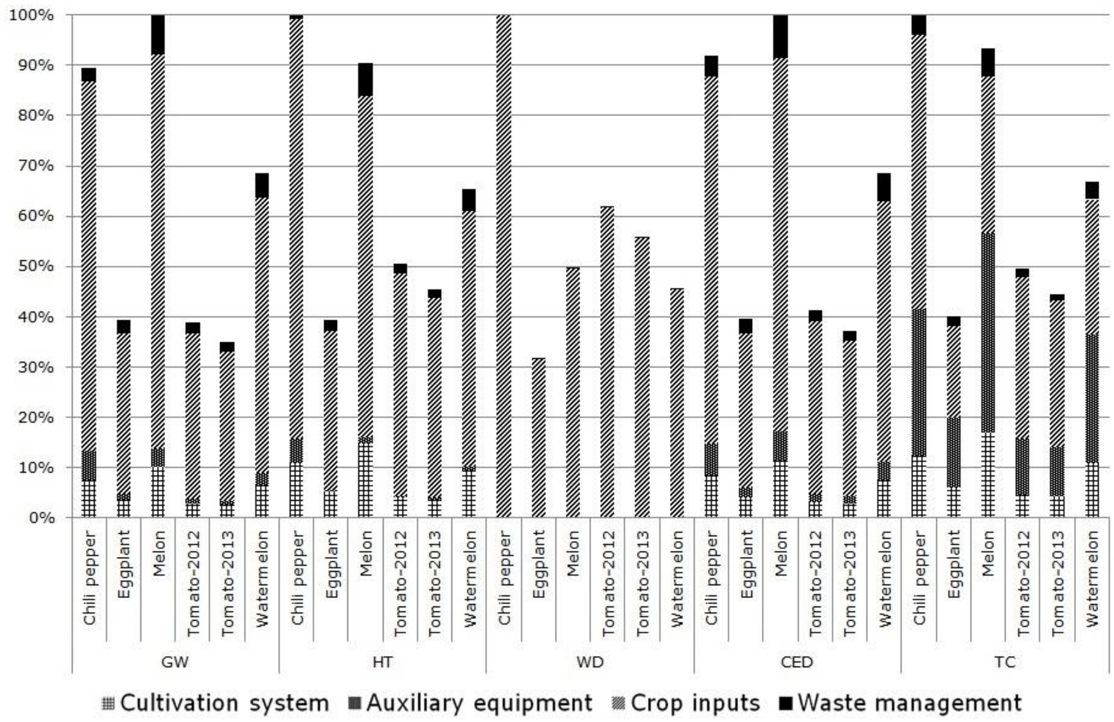


Figure 3: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Chili pepper
Eggplant
Melon
Tomato-2012
Tomato-2013
Watermelon
GW
HT
WD
CED
TC
Cultivation system
Auxiliary equipment
Crop inputs
Waste management

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