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Identifying eco-efficient year-round crop combinations for rooftop greenhouse agriculture

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ABSTRACT

Purpose: Rooftop greenhouses (RTGs) are agricultural systems that can reduce the food supply chain by producing vegetables in unused urban spaces. However, to date, environmental assessments of RTGs have only focused on specific crops, without considering more long-term impacts resulting from seasonality, combinations of crops, and non-operational time. We analyze the production of an RTG over 5 years to determine the crop combinations that minimize yearly environmental impacts while diversifying the food supply.

Methods: The system study consists of an integrated RTG (i-RTG) with hydroponic irrigation in Barcelona (Mediterranean climate). By using life cycle assessment (LCA) with the ReCiPe hierarchical midpoint method, we evaluated the environmental performance of 25 different crop cycles and seven species cultivated during the 2015-2018 period. Two functional units are used: 1 kg of edible fresh production and 1 unit of economic value (€) in the wholesale market. The system boundaries consider two subsystems: infrastructure (greenhouse structure, rainwater harvesting system and auxiliary equipment) and operational (fertilizers and their emissions into water and substrate). In addition, we perform an eco-efficiency analysis, considering the carbon footprint of the crop cycles and their value at the wholesale market during their harvesting periods.

Results and discussion: Spring tomato cycles exerted the lowest impacts in all categories, considering both functional units, due to the high yields obtained. In contrast, spinach and arugula had the highest impacts. Regarding relative impact, the greenhouse structure presented a large impact, while fertilizer production had notable relative contributions in tomato cycles. Moreover, nitrogen and phosphorus emissions from fertigation exerted the majority of the impact on freshwater and marine eutrophication. Growing two consecutive tomato cycles was demonstrated to be the best alternative with the functional unit of yield (0.49 kg CO_2 eq./kg), whereas a long spring tomato cycle combined with bean and lettuce cycles in the autumn was the best scenario with the functional unit of economic value (0.70 kg CO_2 eq./€).

Conclusions: The present study has demonstrated that increasing the diversity of the system leads to better environmental performance of greenhouse urban agriculture if suitable crops are selected for the winter season. The functional unit involving the economic value and the eco-efficiency analysis were useful to demonstrate the capability of the framing system to produce added-value vegetables under harsher conditions, while categorizing and classifying the crops to select the most suitable based on economic and environmental parameters.

KEYWORDS

Urban agriculture; Rooftop greenhouses; Eco-efficiency; Crop combinations; Life Cycle Assessment; Industrial ecology; Urban metabolism; Sustainability

1. Introduction

Due to urban population growth during the last several decades, food supply has become one of the key material flows in the metabolism of cities. This tendency has contributed to an endless increase in environmental impacts, such as greenhouse gas emissions or deforestation processes (Foley et al. 2011). In this context, urban agriculture (UA) is expected to help reduce these impacts while contributing to food security (Mok et al. 2014). Moreover, UA can potentially generate socio-cultural, economic and environmental benefits in urban regions (Thomaier et al. 2015). From an environmental perspective, UA can reduce transport emissions while releasing pressure from agricultural land (Specht et al. 2014). In addition, UA promotes resource efficiency in urban areas. The use of rainwater recovery systems can become an adaptive strategy to mitigate the repercussions of climate change in high-density areas when applied to UA while increasing water supply (Angrill et al. 2012; Petit-Boix et al. 2018b). The re-use of nutrients recovered from urban organic waste (Bryld 2003) and wastewater (de-Bashan and Bashan 2004; Sengupta and Pandit 2011) also offers possibilities to improve the efficiency of UA. In terms of social well-being, UA can reduce the vulnerability of specific urban groups by providing on-demand, fresh, locally grown and pathogen-free food (Despommier 2013) while promoting the development of local economies (Lovell 2010; De Zeeuw 2011; Kortright and Wakefield 2011). In addition, Artmann et al. (2018) highlights the opportunities offered by UA to contribute to biodiversity, ecosystem services and urban regeneration, among others.

For UA to generate these benefits, an understanding of a city's potential to supply different types of food is needed. Not only is UA meant to meet the dietary requirements of the urban population but also to accomplish this goal at the lowest environmental cost. For example, Sanyé-Mengual et al. (2018) analysed the eco-efficiency of an urban home garden in Padua (Italy) and the production of different types of vegetables. The authors presented an innovative home garden that could satisfy the food requirements of 1-2 persons. Although low-tech home gardens can hold some advantages in terms of climate change, they need considerable space, which is scarce in cities (Goldstein et al. 2016). Considering this limitation, research is currently examining the potential benefits of rooftop gardens, a type of UA that takes advantage of unused rooftops to grow vegetables in urban areas.

For example, Sanyé-Mengual et al. (2015b) assessed the performance of a rooftop home garden in Bologna (Italy), concluding that year-round polyculture, i.e., growing a wide variety of vegetables, meets the residents' demand for diversified foods. Similarly, Boneta et al. (2019) found that 8.2 m^2 of rooftop polyculture can cover up to 62% of the average vegetable consumption per capita in the region of Catalonia. In addition to Boneta et al. (2019), Orsini et al. (2014) described the existence of large variations in the yields throughout the year when producing food in urban rooftops, as well as the difficulties found in producing vegetables in cold periods.

To solve this problem, urban rooftop greenhouses (RTGs) are a useful option that benefits from unused roofs (Pons et al. 2015) while allowing year-round production. In particular, integrated RTGs (i-RTG), which are synergetic with the host building, are becoming prominent in recent literature. Sanyé-Mengual et al. (2013) stated that i-RTGs could utilize the waste heat of the building as a heat input without energy requirements, which was later quantified by Nadal et al. (2017). In this sense, some studies have provided insights into the environmental performance of producing tomatoes in i-RTGs. Sanyé-Mengual et al. (2015) compared the performance of an i-RTG with a conventional multi-tunnel greenhouse, finding that the overall impacts were lower for the i-RTG but that its infrastructure had large environmental impacts. Similarly, Sanjuan-Delmás et al. (2018) assessed the performance of i-RTG production by growing three consecutive tomato crops, heated by the building´s residual heat and using rainwater. One of the main findings of this study is the benefits of the synergy between the i-RTG and the building in terms of water using between 80 and 90% of rainwater for the crops. However, to date, i-RTG assessments have only focused on the assessment of specific crops, mainly tomatoes, without accounting for the impacts when the cropping system is not operating. In other words, we know little about how to optimize the time gap between two different crops in i-RTGs because existing experiments have focused on the crop itself but not on the production of additional vegetables once the harvesting period is over or when the cropping system is not operating but is still causing impacts due to the amortization process of the infrastructure.

In this study, we aim to add to this pool of knowledge by exploring how we can tap into the full potential of i-RTGs to produce food throughout the year, strategizing various types of crops to diversify the food supply while further minimizing environmental impacts. To estimate the most eco-efficient crop combinations, we consider the optimal climate conditions, the crop demand, and the market price of individual crops. We also apply the life cycle assessment (LCA) to the various combinations to determine the environmental costs and benefits. Moreover, we also compare the environmental performance of crops with previous literature that considered different systems with the aim of determining where a system such as the i-RTG is located within agricultural systems' environmental behaviour. This analysis is based on data acquired during four years of continuous crop production in an i-RTG located in Barcelona, Spain. Hence, our goal is to assess the agronomic and eco-efficient performance of different crops in different seasons in an i-RTG. Based on a case study, we analyse the yield, environmental impacts and market price of individual crops with the aim of identifying the most eco-efficient crop combination. To this end, we will help urban farmers prioritize more efficient crop combinations for more optimized and sustainable urban agriculture in i-RTGs.

2. Materials and Methods

2.1 System description and experimental crops

The i-RTG under study is located on the top floor of the ICTA-ICP building on the campus of the Universitat Autònoma de Barcelona (41.497681N, 2.108834E) in the Mediterranean region in the northeastern Iberian Peninsula. The i-RTG has an automated bioclimatic outer skin that regulates itself based on climatic parameters, which enables the i-RTG to have a suitable year-round temperature for growing crops. Moreover, the thermal inertia of the entire building accumulates heat in the rooftop, increasing its temperature by 9ºC on average (Nadal et al. 2017). An additional loop of resource optimization of the i-RTG is the water synergy. The i-RTG is equipped with a rainwater harvesting system with 900 m^2 of harvesting surface and a glass fibre reinforced plastic (GFRP) storage tank of 100 m^3.

For this study, we used two of the four 122.8 m^2 greenhouses available in the i-RTG: 1) one facing southeast and with single growing lines and a plant density of 2.0 plants·m^{-2} (LAU1) and 2) one facing southwest and with double growing lines and a plant density of 4.6 plant·m^{-2} (LAU2). Each greenhouse has an area of 88.34 m^2 serviceable for growing crops.

[FIGURE 1]

The irrigation system is hydroponic, supplying a mix of water and nutrients (nutrient solution) to plants through drippers delivering 2 L of solution·h^{-1}. The water is supplied from the 100 m^3 storage tank of the rainwater harvesting system. When there is not enough rainwater, water from the municipal network is used instead. Flowmeters were used to quantify both the irrigated and the drained water. This system allowed us to define two variables. First, the water use efficiency (WUE), which is the total irrigated water per kg of product. Second, the water consumption efficiency (WCE), which is the total water taken up by the plant (including evaporation) per kg of production. Thus, WCE equals WUE minus the water drained from the system.

A total of 25 different crop cycles, seven species and nine different cultivars were grown from March 2015 to December 2018. Those were tomato (*Solanum lycopersicum* var. Arawak variety), lettuce (*Lactuca sativa* vars. green oak, red oak and maravilla), spinach (*Spinacia oleracea* var. space), chard (*Beta vulgaris* var vulgaris), bean (*Phaseolus vulgaris*; var. Pongo), arugula (*Ruca vesicaria*; var. sativa) and pepper (*Capsicum annum*; var. Italian). The crops were chosen based on their representativeness of the Mediterranean diet. Figure 1 shows all the crop cycles, indicating their duration and when they occurred. All lettuce cycles, spinach cycle S3 and arugula cycle R2 were harvested all at once, while the remaining crop cycles were harvested day by day until no longer productive. Tomato cycles T3 and T4 began on

January to analyse the benefit of the temperature difference between the i-RTG and the exterior in contrast to T1 and T2, which started later, coinciding with the typical tomato schedule in the area. The duration of crop cycles, their harvesting periods and other agronomic information can be found in available upon request to the corresponding author.

2.2 Life cycle assessment (LCA)

LCA is a standardized method defined in ISO 14040 (ISO 2006) that is used to determine the environmental performance of products during all life cycle stages, extending from the extraction of raw materials to the end of life. In this section, we will describe the goal and scope, life cycle inventory and impact assessment.

2.2.1 Goal and scope definition

The LCA considered all life cycle stages necessary for crop production, from the extraction of raw materials to the end of life of products. The impacts resulting from the distribution of the horticultural products to the consumers were excluded, considering that they were consumed by the building inhabitants. Figure 2 illustrates the system boundaries. The inventory is split into two main subsystems: infrastructure and operation, as proposed by Sanjuan-Delmás et al. (2018), considering lifespans higher or lower than 5 years, respectively. For waste management, we used cut-off criteria, considering that the benefits and impacts of recycling processes are allocated to the recycled products.

Two different functional units were considered for the assessment:

- **1 kg of edible fresh production**, which consists of the whole plant in the case of lettuce, spinach, arugula and chard, but only fruits when assessing tomatoes, beans and pepper. In this instance, stem, leaves and roots were considered to be residual biomass.
- **1 unit of economic value (€) at the wholesale market**: Obtained by multiplying monthly yield produced in the i-RTG for a specific crop cycle (kg) per monthly prices retrieved from Mercabarna (2018) (€/kg), the local wholesale market. If a crop cycle supplied vegetables for more than one month, the product of the successive multiplications is summed month per month, as shown in Equation 1, where Y and P represent the Yield and the Price, respectively, for a specific Month, represented with an M. Because of the inclusion of different years in this study, using an economic functional unit can help normalize the yield variation between crops grown in different years, as well as typical seasonal variations.

$$Value\ (€)\ = \sum_{i=1}^{n} (Y_{Mi} \cdot P_{Mi}) = (Y_{M1} \cdot P_{M1}) + \cdots + (Y_{Mn} \cdot P_{Mn}) \qquad \text{(Equation 1)}$$

Due to the inclusion of different crops in two different systems (i.e., LAU1 and LAU2), often with different numbers of plants, a normalization process was carried out to obtain comparable results, considering the greenhouse facing the southeast as the reference cropping area. In this sense, the reference crop was set to be in a cropping area with 84.34 m^2 and to have 171 plants in 57 perlite bags, which allow the development and management of all crops analysed.

2.2.2 Life cycle inventory

The infrastructure subsystem includes three different elements, as shown in Figure 2. Greenhouse structure and rainwater harvesting system data were retrieved from previous literature assessing the same system (Sanyé-Mengual et al. 2015a; Sanjuan-Delmás et al. 2018). Data from the auxiliary equipment were acquired by the authors. The operation subsystem includes two items: the substrate for hydroponic cultivation and the fertilizers applied to the crops. The latter also includes the direct emissions to water from the leachates, considering that phosphorus and nitrogen were directly emitted to the environment with the same ratio as drained water. Some elements, such as pump energy, pesticide or nursery plant cultivation, were excluded due to the low impact detected in previous studies (Sanjuan-Delmás et al. 2018).

The end-of-life recycling scenario was assumed for the rainwater harvesting system and the auxiliary equipment. All the components of the greenhouse structure were assumed to be recycled after their lifetime, except for concrete anchors, which were assumed to be landfilled.

An allocation procedure was applied to calculate the fraction of the impacts of the rainwater harvesting system that should be allocated to the crops because the system also supplies water for other uses within the building. Considering the approaches employed by previous studies (Rufí-Salís et al. 2019; Sanjuan-Delmás et al. 2018), we accounted for the total rainwater supplied by the tank (which includes the crops and the building ornamental plants) and the actual rainwater volume used in the crops. In some cases, tap water was used to compensate for rainwater unavailability. In these specific cases, impacts between the rainwater harvesting system and tap water were distributed following a volume allocation.

[FIGURE 2]

The substrate was assumed to be landfilled after three years of use. No wastewater scenario was considered because there was no evidence that the nutrients added through the nutrient solution would be removed in a conventional wastewater treatment plant. The detailed information on the life cycle inventory is available upon request to the corresponding author.

2.2.3 Environmental impact assessment

For the life cycle impact assessment (LCIA), the software SimaPro 8.5 was used. We used the ReCiPe method with a Hierarchical approach (Goedkoop et al. 2009) at the midpoint level to calculate the impacts based on Amani and Schiefer (2011), who recommend this method as the most suitable for the food sector. According to previous literature (Brentrup et al. 2004, Sanjuan-Delmás et al. 2018; Boneta et al. 2019) and the authors' expertise, we used the following impact categories: Climate Change (CC – kg CO_2 eq.), Terrestrial Acidification (TA – kg SO_2 eq.), Freshwater Eutrophication (FE – kg P eq.), Marine Eutrophication (ME – kg N eq.), Fossil Depletion (FDP – kg oil eq.) and Ecotoxicity (ET – kg 1,4-DB eq.) (which includes Marine, Terrestrial and Freshwater Ecotoxicity).

2.3 Eco-efficiency assessment method

ISO 14045 (ISO 2012) defines eco-efficiency assessment as a "*quantitative management tool which enables the study of life-cycle environmental impacts of a product system along with its product system value for a stakeholder*". As stated by Petit-Boix et al. (2018a), ISO 14045 is relatively flexible in terms of methodological approaches. In this sense, the environmental performance of crop cycles was represented by the carbon footprint in kg·CO_2eq/kg (assessed through the climate change impact category with a life cycle perspective). On the other hand, the value assessment was evaluated using the wholesale market price in €·kg^{-1}, considering the average price value during each cycle harvesting period.

The relationship between both parameters was analysed through an eco-efficiency graphical representation to identify the best and worst eco-efficient crops. In this sense, we considered that higher market prices and low environmental impacts were a desired trend, as we are minimizing the carbon footprint while providing food with high added value to the market. This approach was chosen for two reasons. First, periods with higher prices are desired from a commercial perspective. Second, high market prices can become a barrier for access to fresh vegetables to vulnerable communities. Therefore, the provision of local food by means of UA can help overcome this barrier and promote food sovereignty throughout the year.

3. Results

3.1 Agronomic assessment: Yield and water consumption

The experiments conducted in the i-RTG from February 2015 to December 2018 allowed us to define the potential yield of each vegetable crop (Table 1). Average cycle yields vary substantially across cultivated species, with mean productions ranging from 125 g/plant for spinach to 5,858 g/plant for tomato, which was also the most productive crop per day. As expected, seasonal variation affects production, resulting in different yields for the same species (as was especially the case for tomato). Table S1 and Figure S1 in Supplementary Information 1 provide a summary of the statistics for the temperatures inside the i-RTG during all crop cycles. The yield of the tomato winter crop (T5) was between 58 and 74% lower than for tomato crops grown in the warmer season (T1-T4). Moreover, due to the mild temperatures reached in the i-RTG during the winter, the tomato cycle that started earlier (T3) reached a higher yield than the one starting in March (T2) (which would be the common timing for tomato crops) and the one starting in February (T1). Moreover, T3 also had higher yields than T4. Although T4 started on a similar date, it only used one nutrient solution without adapting it to each phenological stage. We can also relate the yield difference between T3 and T4 to temperature values, which were higher and had less variance in T3 than in T4 (Table S1). Table 1 shows that T3 also had the best water use efficiency (WUE) (43 L/kg) and water consumption efficiency (WCE) (24 L/kg) not only compared to other tomato crops but all crops assessed in the i-RTG.

Lettuce was less variable than tomato. Among the lettuce varieties, the red oak cultivar performed the worst in the summer season (L1.R), being the only lettuce cycle with a yield lower than 200 g/plant. Previous literature has also reported yield reduction during heat stress periods for a variety of crops (Porter and Gawith 1999; Wheeler et al. 2000; Prasad et al. 2008). Specifically, Monteiro (1994) highlights the high summer temperature in Mediterranean greenhouses as a potential limitation to crop production. In contrast, the "maravilla" variety performed best, especially in the spring (L3.M) and autumn (L5.M) with yields of 290 and 379 g/plant, respectively. The green oak variety stands out for its yield homogeneity at approximately 225 and 232 g/plant, despite temperature variations (Table S1).

Regarding other crops, Table 1 shows that pepper has the highest yields with 438 g/plant. Nevertheless, considering the length of the crop cycles, lettuce "maravilla" grown in the spring (5.0 g/plant/day) surpassed pepper yield (4.8 g/plant/day). On the other hand, spinach campaigns had the worst performance for WUE and WCE values and the lowest yields, both when it is uprooted during the first harvest (S2 – 57 g/plant) and when it is harvested daily in the summer-autumn season (S3 – 187 g/plant) and in the autumn-winter season (S1 – 131 g/plant). Arugula displayed a similar behaviour when comparing the harvesting method with 102 and 295 g/plant in the summer-autumn season.

[TABLE 1]

3.2 *Environmental performance of the crops*

Table 2 compiles the average environmental impacts of each vegetable crop per unit of yield and economic value. For specific data on environmental impacts per crop cycle, see Table S2 in Supplementary Information 1. The comparison between crops follows a similar trend among impact categories. In this sense, tomato cycles generated the lowest impacts in all categories considering both functional units, except for the tomato cycle grown in the winter (T5), due to its low production. On the other hand, spinach and arugula crop cycles had the greatest impact due to their low yields, especially the cycles uprooted in the first harvest.

Regarding the lettuce crop, Table S2 shows that the lettuce cycle grown in the spring had the lowest impacts. In addition, we can observe that summer cycles had lower impacts than autumn cycles. Moreover, most lettuce cycles had lower environmental impacts than all low-bush crops per kg of yield. However, the bean cycle grown in the summer-autumn season was the cycle that had the lowest impacts among all low-bush crops if the economic value was considered followed by the bean cycle grown in the winter-spring season and the pepper cycle.

[TABLE 2]

Figure 3 shows the impact contribution of the items defined in the inventory on climate change, freshwater eutrophication and marine eutrophication indicators. Eutrophication indicators displayed different trends than climate change, whereas the behaviour of the latter was similar to the remaining indicators shown in Figure S2 of Supplementary Information 1. The impact distribution in tomato crops showed minor differences from the other crops. In climate change, tomato cycles have great contributions from fertilizers and the greenhouse structure (0.19 and 0.24 kg CO_2 eq · kg^{-1}, respectively). The results from the T1 cycle (Table S2) are worthy of special attention because this is the only cycle where fertilizer impacts were higher than those exerted by the greenhouse structure (0.22 vs 0.15 kg CO_2 eq/kg).

On the other hand, the greenhouse structure is the major source of climate change impact in all other crop cycles. However, absolute impacts comprise a wide range of values, ranging from 1.06 in L3.M to 8.44 kg

CO_2 eq/kg in S2 (Table S2). The rainwater harvesting system and the fertilizers had similar impacts in all lettuce, chard, spinach, bean, arugula and pepper cycles, e.g., 0.16 kg CO_2 eq/kg in L3.M, 0.26 kg CO_2 eq/kg in L2.R or 0.31 kg CO_2 eq/kg in C1. This similarity is not observed in L1 cycles, which used tap water. Therefore, no impact from the rainwater harvesting system can be allocated to these cycles.

[FIGURE 3]

3.3 Eco-efficiency analysis

The analysis unveiled five areas of the chart, from best (A) to worst eco-efficiency (E), defined with a slope of 1 and a y-intercept every 2 units of kg CO_2 eq. The four tomato cycles grown in the warmer season and the bean cycle grown in the winter season, the latter due to its high price, were categorized in the A class. The remaining tomato and bean cycles, as well as the chard and pepper cycles and most lettuce cycles, were categorized in the B class, although bean and lettuce crops presented notable differences in economic value. The C class included three autumn lettuce cycles and both arugula cycles. Spinach's low price and high environmental impact make it the only crop within the worst eco-efficiency classes. Figure 4 also shows the variability of the wholesale market price for the different crops and cycles. Lettuce shows the lowest variability between cycles, decoupling the price from the season when it is grown. On the other hand, we can see that tomato cycles presented more variability in terms of price than in the carbon footprint. However, tomato wholesale market price is more affected by year, rather than seasonal variations, as T5 (winter cycle) has a lower price than T3 and T4.

[FIGURE 4]

4. Discussion

4.1 Does i-RTG improve UA for climate change impacts?

4.1.1 Tomato

The impacts of tomato production found in the literature entail a wide range of values, depending on the scope and the place of final consumption. The average impact generated by i-RTG tomato cycles (0.44 kg CO_2 eq. · kg^{-1}) was below many of the values found in the literature, such as 0.49 (outdoor cultivation) and 0.54 kg CO_2 eq/kg (polytunnel) for a community farm (Kulak et al. 2013), or 3.79 (average UK production) and 1.30 kg CO_2 eq/kg (average Europe production without UK) for average UK consumption (Audsley et al. 2010). In addition, i-RTG tomato cycles also scored better than greenhouse production in southern Tehran (0.51 kg CO_2 eq/kg) (Khoshnevisan et al. 2014) and indoor cultivation of a highly specialized company in southern Italy (0.72 kg CO_2 eq/kg) (Cellura et al. 2012). Better results were also found when compared to reports in Denmark (Möller Nielsen 2007) and Sweden (Halberg et al. 2006) (3.45 and 1.30 kg CO_2 eq/kg, respectively).

4.1.2 Lettuce

Similar to the variations among lettuce varieties considered (1.93 ± 0.70 kg CO_2 eq/kg), the environmental impacts of conventional lettuce production show a high dispersion in the literature. Lower impacts were found by Canals et al. (2008) in Spanish outdoor production (0.51 kg CO_2 eq/kg) and in UK-based community farms for both spring (0.34 kg CO_2 eq/kg) and autumn (0.30 kg CO_2 eq/kg) (Kulak et al. 2013). However, impacts exerted by L1.M and L3.M (1.06 kg CO_2 eq/kg) were below some impacts found in previous research, such as 1.15 kg CO_2 eq/kg exerted by Europe and the rest of the world average production (Audsley et al. 2010). More studies were found with considerably higher impacts, such as Shiina et al. (2011) with 6.4 kg CO_2 eq/kg due to high energy consumption from air cooling, or Audsley et al. (2010) with 10 kg CO_2 eq/kg in an average of the rest of the world approach (RoW). The high variability found between cycles could be related to the variability of growing systems and the short cycle of the lettuce crop. In this sense, we found that short-cycle crops tend to be more strongly affected by infrastructure-related impacts. Thus, open-air systems seem to have less impact than more complex systems, such as polytunnel greenhouses or systems with air cooling.

4.1.3 *Other crops*

Spinach was the least efficient crop in terms of environmental performance (6.84 ± 1.83 kg CO_2 eq/kg) compared to previous literature. Impacts of 2.22 and 2.30 kg of CO_2 eq · kg^{-1} were found for Europe averaged (Audsley et al. 2010) and in a specific plant factory (Shiina et al. 2011), respectively. The high impacts of such crops as spinach or arugula can also be related to the normalized setup of the cropping area. Because the setup allows high space-demanding crops, such as tomato or pepper, smaller crops could have been grown with higher densities that will increase the total yield, thereby positively affecting the impacts per functional unit.

On the other hand, better results were found in the literature for pepper, which exerted 2.30 kg CO_2 eq/kg in the i-RTG. For example, Cellura et al. (2012) and Chatzisymeon et al. (2017) showed impacts of 0.84 and 0.14 kg CO_2 eq/kg in a tunnel greenhouse and in the open air, respectively.

Bean production in the i-RTG (3.14 ± 1.10 kg CO2 eq/kg) also had higher impacts compared with the previous literature in both open air and screenhouse (0.36 and 0.17 kg CO_2 eq/kg, respectively) (Romero-Gámez et al. 2012) for different varieties of *Phaseolus vulgaris* in an open-air system in Greece (0.23 ± 0.13 kg CO_2 eq/kg) (Abeliotis et al. 2013), and for UK case studies (1.55 and 1.42 kg CO_2 eq/kg) (Canals et al. 2008). However, the bean cycle grown in the autumn season in the i-RTG (B1 - 2.43 kg CO2 eq/kg) scored better than a bean cycle grown in a greenhouse with a misting system (2.89 kg CO_2 eq/kg) (Romero-Gámez et al. 2012) and different case studies in Africa (10.8 ± 0.14 kg CO_2 eq/kg) (Canals et al. 2008).

4.2 Does i-RTG improve UA in other impact categories?

The majority of the studies found in the literature assessing the environmental performance of crops through LCA focused exclusively on the climate change impact category. Therefore, the possible comparison between the present study and previous results in the literature in the remaining impact categories is very limited. Moreover, the existence of different impact methods among the literature was also a great limitation, as noted by Bach and Finkbeiner (2017). In this sense, different studies were found in the literature that assessed different crops (with a preference for tomato) but used the CML method (e.g. Abeliotis et al. 2013 and Khoshnevisan et al. 2014). Additionally, the inventory of some LCA studies was not present in the manuscripts or the supplementary information, or it was shortened and presented a lack of data, thereby preventing the replicability of the results.

Finally, the following studies were used to compare i-RTG performance in categories different from climate change: Payen et al. (2015), who assessed the production and exportation of tomatoes from Morocco to France (Tomato-M – Table 3) and greenhouse tomato production in France (Tomato-F1), Boulard et al. (2011), who also assessed greenhouse tomato production in France (Tomato-F2 – Table 3), and Fusi et al. (2016), who assessed the impact of fresh cut lettuce in Italy.

Table 3 summarizes the average impacts of i-RTG lettuce and spring tomato crop cycles and the adapted results found in two previous studies. As observed, i-RTG tomato performed better than Tomato-M (3.20 g SO_2 eq) and Tomato-B2 (2.94 g SO_2 eq) in terrestrial acidification but had 64% more impacts than Tomato-F1 (1.28 g SO_2 eq).

[TABLE 3]

Regarding ecotoxicity, tomato and lettuce from i-RTG had greater impacts than the comparable studies (0.62 and 2.3 times more impacts, respectively), due to potassium sulfate fertilizer, the main contributor among fertilizers in ecotoxicity, specifically in freshwater and marine ecotoxicity.

Finally, i-RTG crop cycles also had greater impacts on eutrophication, mainly due to the inclusion in the inventory of the emissions to water from the leachates which, for tomato and lettuce, exerted 90.2 ± 1.3 and 96.4 ± 0.8% of impact in freshwater eutrophication and 89.9 ± 2.5 and 96.1 ± 1.1% of impact in marine eutrophication, respectively. These impacts denote the importance of the need to include this kind of emissions in the inventory for a most precise environmental assessment of eutrophication impacts.

4.3 Towards best annual combination

Considering the impacts of the crop cycles and their classification within the eco-efficiency analysis, we assessed the environmental performance of five scenarios: 0 to 4 (Figure 5). These scenarios combine different crop cycles throughout the year to respond to different perspectives, aiming to improve such parameters as the diversity of the system or its eco-efficiency (considering only crop cycles within A or B eco-efficiency categories in Figure 4).

Due to the high yield obtained and the low environmental impacts, tomato crop cycles are unquestionably the best option to start the year-round crop setup. Moreover, tomato spring cycles also had better yields than other crops tested in the spring season, such as lettuce or bean. Therefore, we defined Scenario 0, which consists of growing a long spring tomato cycle (T3), and Scenario 1, which consists of growing short spring (T1) and winter (T5) tomato cycles.

Nevertheless, planting another tomato cycle is not the only alternative for vertical farming systems in the winter season. First, this step will imply a delay in the following spring cycle planted in the next year, as T5 lasted until late February. Second, similar eco-efficient alternatives within the B cluster (Figure 4) that enrich the crop diversity of the system were found. Using yield as the functional unit, some lettuce cycles showed good performance in the winter, such as L4.M (September) or all L5 varieties (October-November). Additionally, the pepper cycle (P1) had good environmental performance, both with yield and wholesale market price functional units, although better results were found in previous literature. Considering the previous, we defined Scenario 2, which consists of growing a long spring tomato cycle (T3) with two successive lettuce cycles in the winter, and Scenario 3, which consists of growing a long spring tomato cycle (T3) and a pepper cycle in the winter.

On the other hand, a bean cycle from September to November had lower environmental impacts than most winter crop cycles if the wholesale market price is considered as the functional unit due to the scarce availability of this low-bush crop in the market in the winter season. In this sense, Scenario 4 consists of growing a long spring tomato cycle (T3) and a bean and a lettuce cycle in the winter.

The temporal spaces between crop cycles were also considered in the calculations because the aim was to account for the entire year impacts. The temporal space present in all scenarios in August and in scenarios 0, 2, 3 and 4 in December correspond to the summer and winter vacations, respectively, in the university campus under study, but they can be extrapolated elsewhere. The remaining temporal spaces were used for cleaning and setting up the cropping area. For these blank spaces, the rainwater harvesting system impacts were divided by three, considering the existence of 3 systems: the two greenhouses and the ornamental plants.

Figure 5 shows that Scenarios 0 to 4 have similar total life cycle CO_2 eq. emissions, ranging from 881.57 to 901.13 kg CO_2 eq per year in Scenarios 3 and 0, respectively. When the impacts are divided by the functional unit of yield, Scenario 1, which consists of a short tomato spring cycle (T3) followed by a tomato winter cycle (T5), has the lowest environmental impacts (0.49 kg CO_2 eq. $\cdot$ kg^{-1}). Scenarios 2 to 4 exerted an impact of 0.58 kg CO_2 eq. $\cdot$ kg^{-1} and Scenario 0 had an impact of 0.62 kg CO_2 eq. $\cdot$ kg^{-1}, 18% and 27% more than Scenario 1, respectively. On the other hand, the inclusion of the market economic value in the functional unit presents contrasting results. Scenario 4 exerts the lowest environmental impacts with an economic functional unit (0.70 kg $CO_2 \cdot €^{-1}$) due to the high price of bean in the autumn and winter seasons, followed by Scenario 4, with 0.73 kg $CO_2 \cdot €^{-1}$, due to the high price of pepper at the end of the year.

[FIGURE 5]

5. Conclusions

Finding ways to improve the performance of agricultural systems in the framework of urban food supply is crucial for optimizing the future metabolism of cities. The present study assessed environmental performance of rooftop greenhouse production for more eco-efficient urban agriculture. Two main conclusions could be drawn from this analysis.

First, spring tomato cycles were the most productive and efficient option in terms of water usage. Despite its resource intensity in terms of, e.g., fertilizers, they had the best environmental performance among all crops considering functional units of yield and market economic value.

Second, rooftop greenhouses improve urban agriculture by allowing year-round production. Tomato, bean, lettuce or pepper were demonstrated to be good options for the winter season, where agronomic parameters like temperature or radiation tend to be harsher for crop development. Two successive tomato cycles and the combination of a tomato, a bean and a lettuce cycle were the best yearly set-ups with yield and wholesale market price functional units, respectively. In this sense, the inclusion of a functional unit that involves economic parameters and the eco-efficiency analysis were useful to demonstrate the capability of the framing system to produce added-value vegetables in harsher conditions.

In this sense, the present study has demonstrated that increasing the diversity of the system leads to better environmental performance of greenhouse urban agriculture if suitable crops are selected. This finding was validated with the combination of a long productive tomato crop with other added-value crops that can grow in the greenhouse winter conditions, such as green bean or pepper.

Given that this paper presents the environmental performance of different crop cycles grown locally in the framework of urban agriculture, further research is warranted to study the performance of more crops during the winter season and widen the possibilities that urban farmers have to tackle harsher seasons. Moreover, the possibility of growing different crops at the same time could also be worthy of special attention towards more wide-ranging urban agriculture.

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7. Author contributions

All authors were responsible for the conception and design of the study. M. Rufí-Salís, A. Petit-Boix, D. Sanjuan-Delmás, M. Ercilla-Montserrat, G. Villalba and X. Gabarrell conceived the original idea for the study. M. Rufí-Salís, D. Sanjuan-Delmás, M. Ercilla-Montserrat, V. Arcas and F. Parada set up, supervised and acquired the data for the crop cycles. J. Muñoz-Liesa compiled, tidied and classified climatic data. M. Rufí-Salís analysed the data, performed the LCA, and took the lead in writing the manuscript. All authors critically revised the draft for important intellectual content. All authors gave their final approval to the manuscript.

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TABLES

Table 1. Yields (fresh weight) and water parameters of the crop cycles. SE: Southeasterly facing; SO: Southwesterly facing; DAT: Days After Transplanting; Yield^1: per cycle in g/plant ± Standard Deviation (calculated per lines in tomato and bean); Yield^2: per crop in g/plant/day ± Standard Deviation; Yield^3: per crop (average) in g/plant ± Standard Deviation; WUE: Water Use Efficiency, in L/kg; WCE: Water Consumption Efficiency, in L/kg; RWU: Rainwater used, in %; *T: Tomato; L: Lettuce; .G: Green Oak Lettuce; .R: Red Oak Lettuce; .M: Maravilla Lettuce; B: Green Bean; S: Spinach; C: Chard; R: Arugula; P: Green Pepper.*

Crop	**Cycle**	**Season**	**Face**	**DAT**	Yield^1	Yield^2	Yield^3	WUE	WCE	RWU
Tomato	T1	Wi-Sp-Su	SE	163	7,197 ± 1,365	44.2 ± 8.4	5,858 ± 2,388	64	42	82
	T2	Wi-Sp-Su	SE	139	5,179 ± 1,526	37.3 ± 11.0		47	26	90
	T3	Wi-Sp-Su	SE	187	8,463 ± 334	45.3 ± 1.8		43	24	89
	T4	Wi-Sp-Su	SE	208	6,279 ± 1,093	30.2 ± 5.3		72	46	100
	T5	Su-Au-Wi	SE	171	2,170 ± 632	12.7 ± 3.7		104	71	88
Lettuce	L1.G	Su	SO	32	232 ± 88	7.3 ± 2.7	247 ± 60	52	31	0
	L1.R	Su	SO	32	174 ± 106	5.4 ± 3.3		70	41	0
	L1.M	Su	SO	32	285 ± 82	8.9 ± 2.6		43	25	0
	L2.G	Au	SO	36	225 ± 29	6.2 ± 0.8		96	67	100
	L2.R	Au	SO	36	251 ± 30	7.0 ± 0.8		86	60	100
	L2.M	Au	SO	36	223 ± 9	6.2 ± 0.2		97	68	100
	L3.M	Sp	SO	34	379 ± 70	11.1 ± 2.1		54	38	100
	L4.M	Su-Au	SE	32	259 ± 35	5.4 ± 1.1		74	52	100
	L5.G	Au	SO	57	231 ± 36	4.1 ± 0.6		148	58	100
	L5.R	Au	SO	62	225 ± 43	3.7 ± 0.7		165	64	100
	L5.M	Au	SO	63	290 ± 76	5.0 ± 1.2		120	47	100
Spinach	S1	Au-Wi	SO	83	131 ± 22	1.6 ± 0.3	125 ± 65	380	149	100
	S2	Su-Au	SE	40	57 ± 20	1.4 ± 0.5		424	297	100
	S3	Su-Au	SE	83	187 ± 23	2.3 ± 0.3		267	187	100
Chard	C1	Au	SO	57	328 ± 44	5.8 ± 0.8	328	181	139	100
Bean	B1	Su-Au	SE	57	256 ± 47	4.6 ± 0.8	283 ± 38	152	86	100
	B2	Wi-Sp	SO	119	309 ± 10	2.6 ± 0.1		231	104	100
Arugula	R1	Su-Au	SE	34	102 ± 22	3.0 ± 0.7	198 ± 136	201	141	100
	R2	Su-Au	SE	83	295 ± 57	3.5 ± 0.7		169	118	100
Pepper	P1	Su-Au	SE	92	438 ± 119	4.8 ± 1.3	438	126	88	100

Table 2. Average environmental Impacts of crops. IC: Impact Category; CC: Climate Change; TA: Terrestrial Acidification; FE: Freshwater Eutrophication; ME: Marine Eutrophication; FDP: Fossil Depletion; ET: Ecotoxicity.

IC	Unit	Tomato	Lettuce	Spinach	Chard	Bean	Arugula	Pepper
CC	kg CO_2 eq/kg	5.7E-01	1.9E+00	6.8E+00	2.1E+00	3.1E+00	3.3E+00	2.3E+00
	kg CO_2 eq/€	6.4E-01	3.3E+00	8.4E+00	3.2E+00	1.1E+00	4.0E+00	2.0E+00
TA	kg SO_2 eq/kg	2.7E-03	8.3E-03	3.0E-02	8.9E-03	1.4E-02	1.4E-02	1.0E-02
	kg SO_2 eq/€	3.0E-03	1.4E-02	3.7E-02	1.4E-02	4.9E-03	1.7E-02	8.9E-03
FE	kg P eq/kg	1.8E-04	5.3E-04	1.9E-03	5.6E-04	9.1E-04	9.5E-04	6.5E-04
	kg P eq/€	2.0E-04	9.2E-04	2.3E-03	8.6E-04	3.3E-04	1.1E-03	5.8E-04
ME	kg N eq/kg	1.6E-04	4.8E-04	1.8E-03	5.2E-04	7.7E-04	8.4E-04	5.8E-04
	kg N eq/€	1.8E-04	8.3E-04	2.2E-03	8.0E-04	2.8E-04	1.0E-03	5.2E-04
FDP	kg oil eq/kg	1.6E-01	5.8E-01	2.1E+00	6.2E-01	9.7E-01	1.0E+00	7.1E-01
	kg oil eq/€	1.8E-01	1.0E+00	2.6E+00	9.5E-01	3.5E-01	1.2E+00	6.4E-01
ET	kg 1,4-DB eq/kg	1.5E-02	3.8E-02	1.3E-01	4.0E-02	6.1E-02	6.5E-02	4.4E-02
	kg 1,4-DB eq/€	1.7E-02	6.6E-02	1.6E-01	6.2E-02	2.2E-02	7.8E-02	4.0E-02

Table 3. Impact per kg of i-RTG tomato, lettuce and pepper cycles and from these crops in previous literature in terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), fossil depletion (FDP) and ecotoxicity (ET). Data in format x ± y, represent average ± standard deviation (SD). Average and SD for tomato crop in the i-RTGs calculated considering spring crops (T1 – T4).

Study	Crop	TA [g SO_2 eq]	FE [g P eq]	ME [g N eq]	FDP [kg oil eq]	ET [g 1,4-DB eq]
I-RTG	Tomato	2.10 ± 0.24	0.83 ± 0.02	1.81 ± 0.11	0.12 ± 0.40	12.04 ± 1.85
	Lettuce	8.35 ± 3.06	1.42 ± 0.77	2.87 ± 2.06	0.58 ± 0.21	38.17 ± 13.46
Payen et al. (2015), adapted	Tomato-M	3.20	0.17	0.21	0.20	7.42
	Tomato-F1	1.28	0.11	0.05	-	-
Boulard et al. (2011)	Tomato-B2	2.94	0.18	0.96	-	-
Fusi et al. (2016), adapted	Lettuce	10.84	0.27	0.79	0.48	11.60

FIGURE CAPTIONS

Figure 1. Crop cycles considered in the study. T – Tomato; L – Lettuce; .G – Green oak variety; .R – Red oak variety; .M – Maravilla variety; B – Green bean; S – Spinach; C – Chard; R – Arugula; P - green pepper.

Figure 2. System boundaries of the System under studyour assessment divided into infrastructure and operation. Adapted from Rufí-Salís et al. (2019)

Figure 3. Average relative Climate Change (CC), Freshwater Eutrophication (FE) and Marine Eutrohication (ME) impact contribution per item of crops grown in the 2015-2018 period.

Figure 4. Eco-efficiency of i-RTG crop cycles for climate change (CC) against the price of the crops in the market. T – Tomato; L – Lettuce; .G – Green oak lettuce; .R – Red oak lettuce; .M – Maravilla lettuce; B – Green bean; S – Spinach; C – Chard; R – Arugula; P - green pepper.

Figure 5. Crop calendar of Scenarios 0-4 and their impact in Climate Change. T – Tomato; L – Lettuce; .G – Green oak lettuce; .R – Red oak lettuce; .M – Maravilla lettuce; B – Green bean; S – Spinach; C – Chard; R – Arugula; P - green pepper; N – no crops.

FIGURES

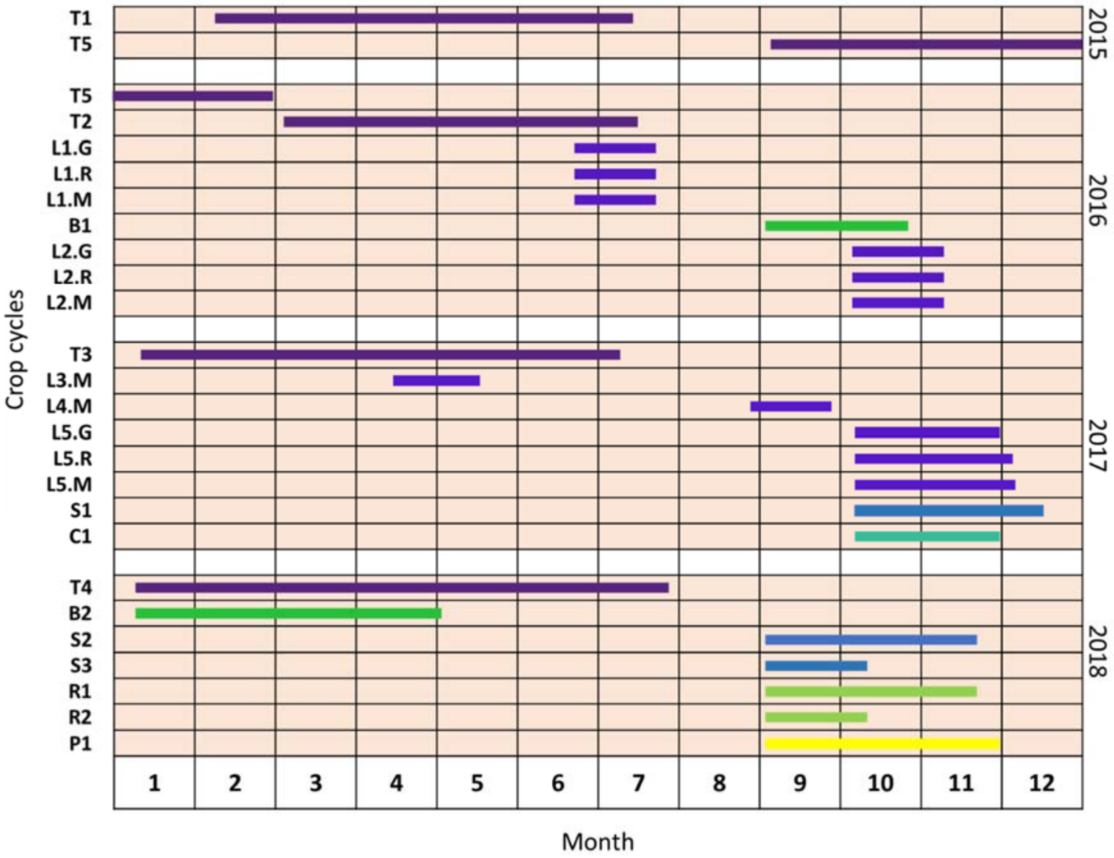
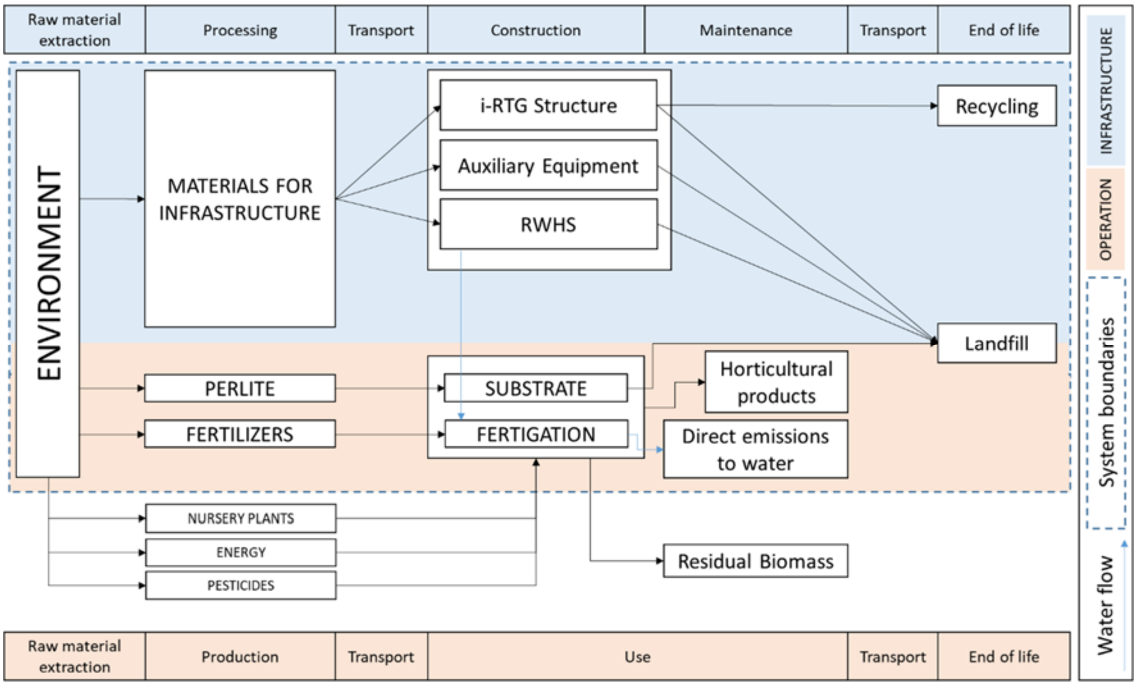


Figure 1. *Crop cycles considered in the study. T – Tomato; L – Lettuce; .G – Green oak variety; .R – Red oak variety; .M – Maravilla variety; B – Green bean; S – Spinach; C – Chard; R – Arugula; P - green pepper.*



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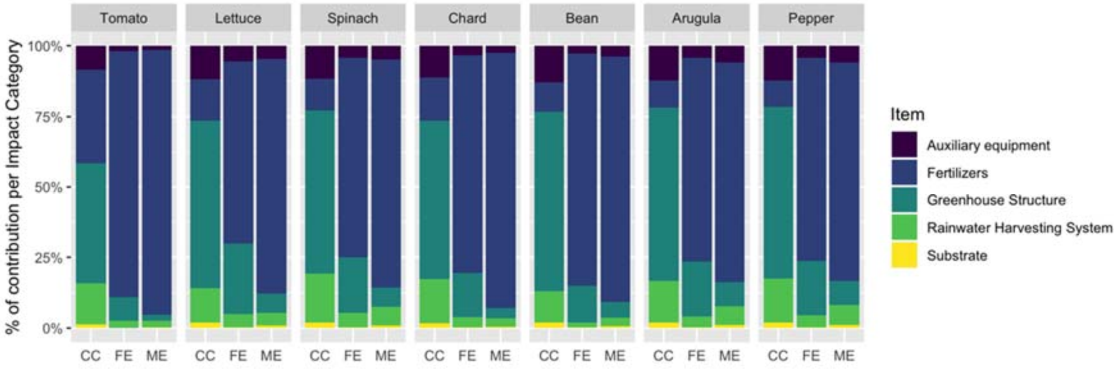

Figure 3. *Average relative Climate Change (CC), Freshwater Eutrophication (FE) and Marine Eutrohication (ME) impact contribution per item of crops grown in the 2015-2018 period.*

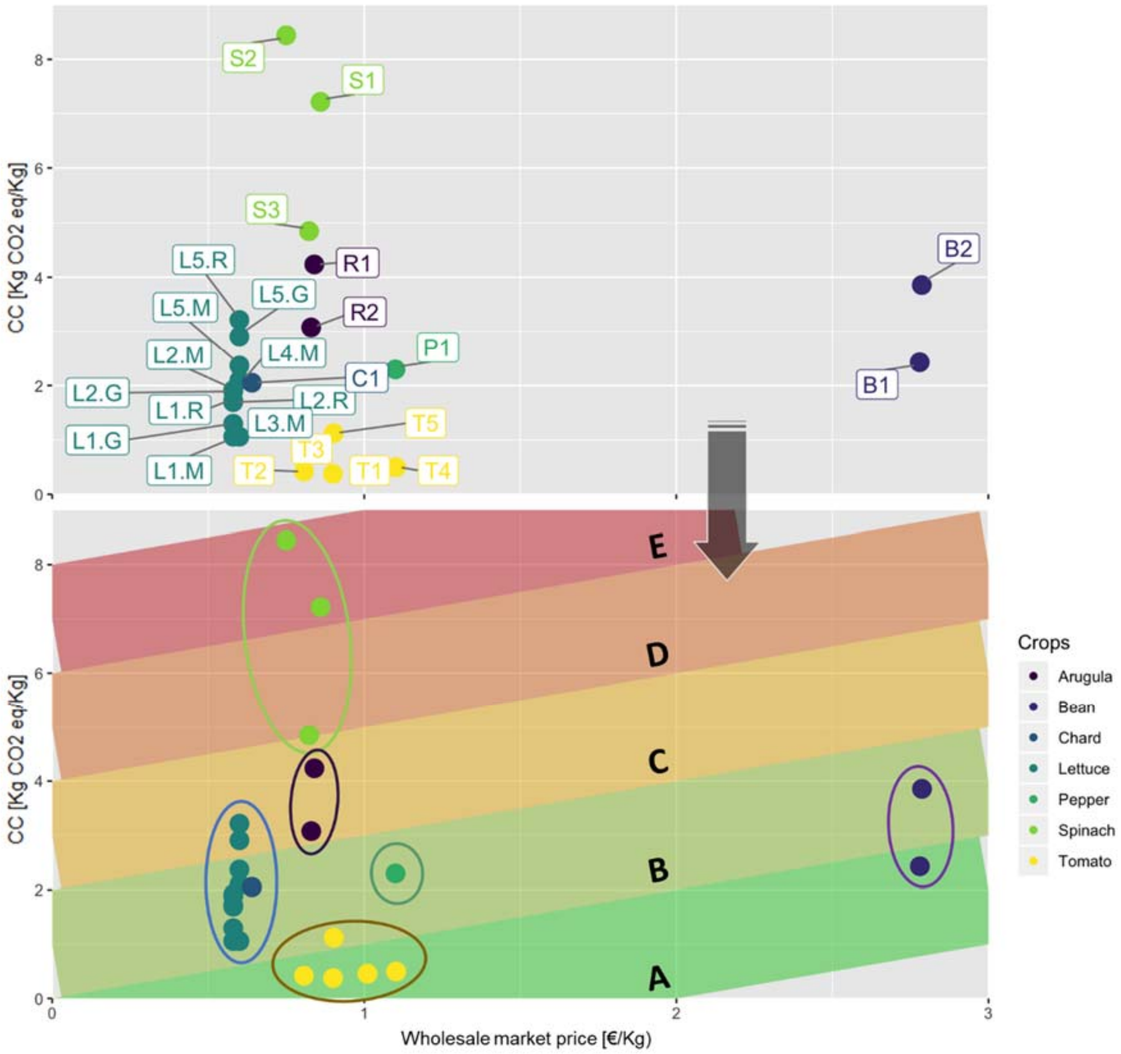

Figure 4. *Eco-efficiency of i-RTG crop cycles for climate change (CC) against the price of the crops in the market. T – Tomato; L – Lettuce; .G – Green oak lettuce; .R – Red oak lettuce; .M – Maravilla lettuce; B – Green bean; S – Spinach; C – Chard; R – Arugula; P - green pepper.*

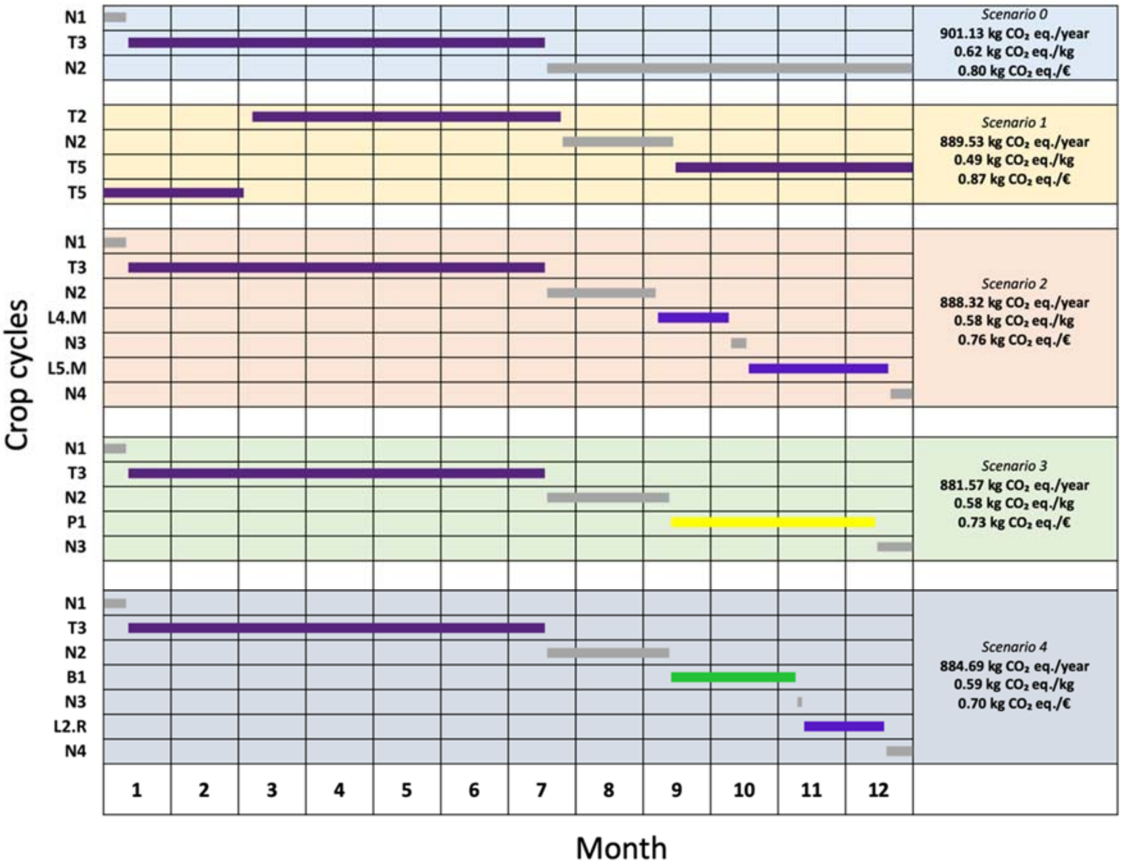

Figure 5. *Crop calendar of Scenarios 0-4 and their impact in Climate Change. T – Tomato; L – Lettuce; .G – Green oak lettuce; .R – Red oak lettuce; .M – Maravilla lettuce; B – Green bean; S – Spinach; C – Chard; R – Arugula; P - green pepper; N – no crops.*