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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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34 **Abstract.**

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

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

46 **Results:** For leafy vegetables, most environmentally-friendly options were the floating
47 technique in summer crops (65-85% lower) and substrate production in winter (85-95% lower),
48 while in substrate production, eggplants and tomatoes were the fruit vegetables that showed best
49 environmental performances ($\approx 74 \text{ g CO}_2 \cdot \text{kg}^{-1}$). From the economic point of view, floating
50 production was 25% cheaper in summer and substrate was 65% cheaper than NFT production of
51 lettuce, while substrate production of eggplants resulted in the cheapest crop ($0.13 \text{ €} \cdot \text{kg}^{-1}$). We
52 here demonstrate that URF production is an environmentally-friendly option for further develop
53 urban local production. We recommend that community URF designs include re-used elements
54 and promote horticultural knowledge to improve their sustainability performance.

55

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

58

59

60 **1. INTRODUCTION**

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

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

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

86 Notwithstanding the sustainable image of URF, only a few studies have focused on the
87 quantification of their environmental, economic and social impacts. Astee and Kishnani (2010)
88 analyzed the potential domestic vegetable production of rooftop farming in Singapore and the
89 resulting CO₂ savings by reduced food imports. In the same line, Sanyé-Mengual et al. (2015a)
90 evaluated the potential RTG implementation in industrial parks in Barcelona through a GIS-
91 LCA guide, which includes a self-sufficiency and environmental assessment of local
92 production. Sanyé-Mengual et al. (2013) quantified the environmental benefits of the local
93 supply-chain of tomatoes produced in rooftop greenhouses (RTGs) in Barcelona (Spain) and
94 contrasted with the conventional supply-chain of tomatoes from Almeria (Spain). Sanyé-
95 Mengual et al. (2015b) accounted for the environmental burdens of the structure of an RTG and
96 compared it to a conventional greenhouse, since more resources are consumed for reinforcing

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

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

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

126

127 **2. MATERIALS AND METHODS**

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

131

132 **2.1. Experimental crops**

133 Experimental trials were performed from April 2012 to January 2014 in the rooftop of a public
134 housing building in the city of Bologna (Italy). Bologna is a representative case study of
135 Mediterranean cities, where climatic conditions are favorable for year-round open-air rooftop
136 farming practices. The experimental crops were performed in a community garden implemented
137 on the 250 m² terrace of the 10th floor of the building. Three different cultivation systems were
138 used in the trials: modified NFT, floating and substrate (illustrated in Fig. 1). The modified NFT
139 (Fig. 1a) was done on re-used PVC pipes, where leafy vegetables were placed in net pots to be
140 in contact with the nutrient solution, which was recirculated and supported with additional
141 irrigation. The floating system (Fig. 1b) consisted of a wooden container (made of re-used
142 pallets and waterproofed with a plastic film), filled with the nutrient solution that was
143 oxygenated with an aerator, where plants were grown on net-pots placed on a floating
144 polystyrene board. Substrate production (Fig. 1c) was also done on wooden containers where
145 plants were grown on commercial soil with compost and fertilizers. Tap water was used for
146 irrigation in all the systems since rainwater harvesting (RWH) system were not considered in
147 the design. Trials were performed for six crops including leafy and fruit vegetables: lettuce
148 (*Lactuca sativa* L.), tomato (*Solanum lycopersicum* L.), melon (*Cucumis melo* L.), watermelon
149 (*Citrollus lanatus* Thumb.), chili pepper (*Capsicum annuum* L.) and eggplant (*Solanum*
150 *melongena* L.) (Fig. 1). Leafy vegetables were cultivated in NFT, floating and substrate, while
151 fruit vegetables were only grown in substrate. Crop cycles are indicated in Fig. 1 as Days-After-
152 Transplanting (DAT) values. Other vegetables although not included in this analysis, were
153 grown year-round in the garden. In particular, chicory and black cabbage were initially
154 considered for assessing leafy vegetables production although were finally excluded due to low
155 crop yield values.

156

157 **2.2. Life Cycle Assessment**

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

160

161 **2.2.1. Goal and scope**

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

167

168 **2.2.2. Life Cycle Inventory (LCI)**

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

173

174 *(a) Cultivation systems and auxiliary equipment*

175 The cultivation systems included in the analysis are modified NFT in PVC pipes, floating in
176 wood container and substrate in wood container (Fig. 1). Type and amount of materials are
177 obtained from the experimental trials in Bologna and the designs detailed in Marchetti et al.
178 (2012). Wood containers are made of re-used pallets while former PVC pipes are used in the
179 NFT system. When materials are re-used, the environmental impacts of their extraction and
180 manufacturing are excluded from the assessment as they belong to the former product. The
181 auxiliary equipment includes all the elements related to the irrigation system required for each
182 crop. Pumps and timer materials are excluded from the system boundaries due to the low
183 repercussion per functional unit, based on a mass cut-off criterion. LCI data is compiled in Tab.
184 1. LCI background data for materials extraction, processing, transportation and electricity
185 generation are obtained from ecoinvent 2.2. database (Swiss Center for Life Cycle Inventories
186 2010). Since the cultivation systems are used year-round for multiple crops, their impact is
187 allocated for each crop product according to their crop cycle (indicated as Days-After-
188 Transplanting values in Figure 1).

189

190 *(b) Crop inputs*

191 Crop inputs depend on cultivation system and crop. First, water consumption is determined by
192 cultivation system, crop, plant density and crop cycle. For substrate cultivation, irrigation is of
193 $11.7 \text{ L}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ for tomato and lettuce, $4.7 \text{ L}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ for eggplant, $7.2 \text{ L}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ for chili pepper,
194 $2.6 \text{ L}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ for melon and $3.7 \text{ L}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ for watermelon. For NFT, crops are irrigated with the
195 nutrient solution through a recirculation system at a rate of $1.9 \text{ L}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ in autumn-winter
196 cycles and of $3.9 \text{ L}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ in summer cycles. For floating cultivation, the container is filled
197 with the nutrient solution and losses per evapotranspiration are replaced, resulting into a
198 consumption of $1.3 \text{ L}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ in autumn-winter cycles and of $4 \text{ L}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ in summer cycles.
199 Energy consumption includes the requirements for the irrigation timer, the recirculation pump
200 (i.e., NFT) and the aerator (i.e., floating).

201 Fertilizers are supplied in a solid form in substrate cultivation and as a nutrient solution in NFT
202 and floating. For substrate, $30 \text{ g}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$ of N-P-K 15-5-20 with $2 \text{ g}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$ of MgO and
203 micronutrients are yearly supplied. For NFT and floating, the nutrient solution contains the
204 following fertilizers: NPK ($80 \text{ mg}\cdot\text{L}^{-1}$), CaNO_3 ($30 \text{ mg}\cdot\text{L}^{-1}$) and KNO_3 ($40 \text{ mg}\cdot\text{L}^{-1}$). Substrate
205 cultivation is done on potting soil, where compost is added to regenerate it and to complete

206 fertilization at a rate of $210 \text{ g}\cdot\text{m}^{-2}$ of soil. Compost is made by the rooftop garden users by
207 composting the biowaste from crops and their own organic waste. Plants in NFT and floating
208 systems are placed on net pots with a mix of substrates: perlite (1/3), coconut fiber (1/3) and
209 expanded clay (1/3). All crops are pesticide-free.

210 LCI data is obtained from the experimental trials, detailed in Orsini et al. (2014) and Marchetti
211 (2012). LCI data for home composting of green biowaste is obtained from Colón et al. (2010).
212 Background data for the LCI is completed from the ecoinvent 2.2. database (Swiss Center for
213 Life Cycle Inventories 2010) and the LCA Food database (Nielsen et al. 2003).

214

215 *(c) Waste management*

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

221

222 *(d) Cost data*

223 Costs of the different materials and elements of the cultivation systems and auxiliary equipment
224 are obtained from suppliers, as well as for substrate and fertilizers. Tap water cost is 0.00153
225 $\text{€}\cdot\text{L}^{-1}$, according to Bologna's supplier (Gruppo Hera). Electricity cost is $0.1539 \text{ €}\cdot\text{kWh}^{-1}$
226 (EUROSTAT 2014). Transportation cost is $0.003 \text{ €}\cdot\text{kgkm}^{-1}$, according to the transport type,
227 consumption rate and current fuel prices. Material costs of re-used elements are considered as 0,
228 although the related transportation and construction requirements are accounted for.

229

230 **2.2.3. Sensitivity assessment**

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

239 Second, community and private gardens can be used seasonally, leading to a low use intensity
240 (e.g., only summer crops), or can be year-round thereby combining autumn-winter and spring-
241 summer crop cycles. A "Low use intensity scenario" assumes that only one crop is done during

242 the entire year and, therefore, the environmental impacts and costs of the cultivation system of
243 the entire year are allocated to one crop.

244

245 **2.2.4. Life Cycle Impact Assessment (LCIA)**

246 The environmental impact assessment is performed by applying the LCIA stage. The SimaPro
247 7.3.3 software (PRé Consultants 2011) is used to conduct the LCIA, which follows
248 classification and characterisation steps determined as mandatory by the ISO 14044 regulation
249 (ISO 2006). The LCIA is carried out at the midpoint level, and methods applied are the ReCiPe
250 (Goedkoop et al. 2009) and cumulative energy demand (CED) (Hischier et al. 2010). With
251 respect to the ReCiPe, the hierarchical time perspective is considered, as recommended in the
252 ILCD Handbook (EC-JRC 2010). The environmental indicators include the global warming
253 (GW, kg CO₂ eq), the water depletion (WD, m³) and the cumulative energy demand (CED, MJ).
254 Besides, the human toxicity potential (HT, kg 1.4-DB eq.) is used to evaluate potential effects
255 on human health. The LCC assessment considers the cost of the systems and results are shown
256 through the total cost (TC, €) indicator.

257

258 **3. RESULTS AND DISCUSSION**

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

265 Table 2 compiles the environmental and economic results for the production of fruit and leafy
266 vegetables in the rooftop garden. Substrate production of eggplant and tomato obtained the
267 lowest environmental impact in global warming (0.073 kg CO₂eq·kg⁻¹), human toxicity (0.027
268 kg 1-4DBeq·kg⁻¹) and energy consumption (1.20 MJ·kg⁻¹), while eggplant was the cheapest
269 crop (0.17 €·kg⁻¹). Lettuce production in floating technique was the most water efficient
270 production (<0.04 m³·kg⁻¹). On the contrary, lettuce production in NFT was the most expensive
271 (1.47 €·kg⁻¹, on average) and the most impacting crop in global warming (3.78 kg CO₂eq·kg⁻¹,
272 on average), human toxicity (0.84 kg 1-4DBeq·kg⁻¹, on average) and energy consumption (57.1
273 MJ·kg⁻¹, on average), because of the large energy consumption of the recirculation pump and
274 the low crop yield (1.3 kg·m⁻², on average). Finally, lettuce production in substrate consumed
275 the largest amount of water (0.39 m³·kg⁻¹) since substrate production is the least water efficient
276 system and crop yield was low (1.5 kg·m⁻²). When correlating these results with the agronomic
277 data, relation to crop yield and crop period were moderately significant (R²>0.6). The lower the
278 crop yield and the longer the crop period, the higher the environmental impacts and costs.

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

287

288 **3.1. Comparing cultivation techniques for leafy vegetables**

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

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

299 For lettuce production in winter, substrate was the more environmentally-friendly and cheaper
300 option, apart from the water depletion indicator where the floating technique consumed the
301 lowest amount per kg (0.04m³·kg⁻¹). Electricity consumption for irrigation purposes was the
302 lowest in substrate production (i.e., timer), compared to the other systems where the use of
303 electric devices is more intensive (i.e., recirculation pump, aerator). However, water
304 consumption in substrate production was 10 times larger because of a longer crop cycle, a lower
305 crop yield (1 kg·m⁻², the lowest of the three techniques) and larger irrigation requirements per
306 kg of product. In particular, substrate production of leafy vegetables became a water inefficient
307 system, since the irrigation rate (1.3L·day⁻¹·plant⁻¹) was the same as for some fruit vegetables
308 (e.g., tomato). Thus, leafy vegetables were irrigated at a fruit vegetable rate although their water
309 requirements are lower. This is caused by the simultaneous production of multiple vegetables,
310 while in a monoculture design water requirements would be crop-specific.

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

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

325

326 **3.2. Substrate production of fruit vegetables**

327 Figure 3 displays the environmental impact and economic cost of substrate production of fruit
328 vegetables. These crops had a global warming impact ranging from 68 to 194 g of CO₂ eq., a
329 human toxicity impact between 0.02 and 0.7 kg 1-4DB eq, a water depletion between 50 to 158
330 L, and an energy consumption between 1.14 a 3.05 MJ. Total costs per kg varied from 0.17€ to
331 0.44€, being the crop inputs the major cost (52%, on average) (Tab. 2). The life cycle stage that
332 contributed the most to the environmental indicators turned out to be the irrigation (≈ 70%),
333 particularly in water depletion where it accounted for almost the 100%. Within the irrigation
334 system, the consumption of tap water was the main contributor to the water depletion (≈ 52%)
335 and economic cost (≈ 80%), while the electricity consumed by the pump and the timer was the
336 main cause (45-65%) of the other environmental indicators.

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

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

353

354 **3.3. Cultivation systems design: sensitivity assessment of availability of re-used materials**
355 **and use intensity of the garden**

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

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

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

383 For lettuce (multiple crop cycles), the sensitivity to use intensity and availability of re-used
384 materials was related to crop yield and crop period values. On NFT, the variation in the
385 environmental impact of lettuce production was strictly related to the crop yield ($R^2 > 0.99$). The
386 higher the crop yield, the lower the variation in the environmental indicators. On the contrary,
387 the sensitivity to the availability of re-used elements for the design depended on the crop period
388 ($R^2 \approx 0.8$). The shorter the crop period, the lower the increase in the environmental indicators

389 when using new materials. The same trends were found for lettuce production in floating
390 technique.

391

392 **4. CONCLUSIONS**

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

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

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

418 Notwithstanding the potential benefits of open-air rooftop farming, the design of the cultivation
419 system and the crop planning are crucial points to optimize the environmental and economic
420 performance of these systems. Rooftop farming design may focus on the potential local
421 resources that can be used in the construction stage, particularly on those elements that can have
422 a second life in the garden through re-use (e.g., pallets, pipes, wheels). Moreover, the design
423 may include different type of cultivation systems. This is because fruit and leafy vegetables
424 have different requirements. According to the results, we would recommend the use of substrate
425 techniques for fruit vegetables and winter cycles of leafy vegetables, while floating production

426 would be interesting for summer crops of leafy vegetables. On the contrary, NFT would be the
427 least recommended option. Regarding management, crop planning may focus on selecting the
428 vegetables (e.g., combination of fruit vegetables with higher crop yield and leafy vegetables)
429 and establishing crop periods to diversify the production during spring-summer and fall-winter
430 cycles, thereby producing year-round and reducing the environmental impacts and economic
431 costs of crops. Further research may focus on applying social indicators in URF future studies or
432 integrate social services as positive externalities in the overall economic balance.

433

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446

447 REFERENCES

448 Astee L, Kishnani N (2010) Building Integrated Agriculture: Utilising Rooftops for Sustainable Food
449 Crop Cultivation in Singapore. *J green Build* 5:105–113.

450 Cerón-Palma I, Sanyé-Mengual E, Oliver-Solà J, et al. (2012) Barriers and Opportunities Regarding the
451 Implementation of Rooftop Eco.Greenhouses (RTEG) in Mediterranean Cities of Europe. *J Urban*
452 *Technol* 19:87–103.

453 Colón J, Martínez-Blanco J, Gabarrell X, et al. (2010) Environmental assessment of home composting.
454 *Resour Conserv Recycl* 54:893–904.

455 EC-JRC (2010) International Reference Life Cycle Data System (ILCD) handbook: General guide for
456 Life Cycle Assessment - Detailed guidance.

457 EUROSTAT (2014) Energy statistics. <http://epp.eurostat.ec.europa.eu/>. Accessed 2 May 2014

458 FAO (2013) Good Agricultural Practices for Greenhouse Vegetable Crops: Principles for Mediterranean
459 Climate Areas. 636.

460 Goedkoop M, Heijungs R, Huijbregts M, et al. (2009) ReCiPe 2008, A life cycle impact assessment
461 method which comprises harmonised category indicators at the midpoint and the endpoint level; First
462 edition Report I: Characterisation. Ministerie van VROM, Den Haag

463 Grewal SS, Grewal PS (2012) Can cities become self-reliant in food? *Cities* 29:1 – 11.

464 Hirschier R, Weidema B, Althaus H, et al. (2010) Implementation of Life Cycle Impact Assessment
465 Methods. Final report ecoinvent v2.2 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf

- 466 ISO (2006) ISO 14040: Environmental management - Life cycle assessment - Principles and
467 framework. International Organization for Standardization, Geneva
- 468 ISO (2008) ISO 15686-5: Buildings and constructed assets - Service-life planning - Part 5: Life-cycle
469 costing.
- 470 Local action on Food (2012) A Growing Trade. A guide for community groups that want to grow and
471 sell food in our towns and cities. 80.
- 472 Marchetti L (2012) Above our heads , below the sky : a step-by- step procedure for creating and
473 managing a soilless roof community garden. Alma Mater Studiorum Università di Bologna
- 474 Mok H-F, Williamson VG, Grove JR, et al. (2013) Strawberry fields forever? Urban agriculture in
475 developed countries: a review. *Agron Sustain Dev* 24:21–43.
- 476 Nielsen, Nielsen A, Weidema B, et al. (2003) LCA food data base.
- 477 Orsini F, Gasperi D, Marchetti L, et al. (2014) Exploring the production capacity of rooftop gardens
478 (RTGs) in urban agriculture: the potential impact on food and nutrition security, biodiversity and other
479 ecosystem services in the city of Bologna. *Food Secur* 6:781–792.
- 480 Pennisi G (2014) Sistemi fuorisuolo per l' orticoltura in città : casi studio nella città di Bologna. Alma
481 Mater Studiorum Università di Bologna
- 482 PRé Consultants (2011) SimaPro software version 7.3.3.
- 483 Sanjuan-Delmás D, Petit-Boix A, Gasol CM, et al. (2014) Environmental assessment of drinking water
484 transport and distribution network use phase for small to medium-sized municipalities in Spain. *J Clean*
485 *Prod.* doi: 10.1016/j.jclepro.2014.09.042
- 486 Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, et al. (2013) Environmental analysis of the logistics of
487 agricultural products from roof top greenhouses in Mediterranean urban areas. *J Sci Food Agric* 93:100–
488 109.
- 489 Sanyé-Mengual E, Oliver-Solà J, Montero JI, Rieradevall J (2015) An environmental and economic life
490 cycle assessment of Rooftop Greenhouse (RTG) implementation in Barcelona, Spain. Assessing new
491 forms of urban agriculture from the greenhouse structure to the final product level. *Int J Life Cycle*
492 *Assess.* doi: 10.1007/s11367-014-0836-9
- 493 Specht K, Siebert R, Hartmann I, et al. (2014) Urban agriculture of the future: an overview of
494 sustainability aspects of food production in and on buildings. *Agric Human Values* 31:33–51.
- 495 Swiss Center for Life Cycle Inventories (2010) Ecoinvent Data v2.2.
- 496 Thomaier S, Specht K, Henckel D, et al. (2014) Farming in and on urban buildings: Present practice and
497 specific novelties of Zero-Acreage Farming (ZFarming). *Renew Agric Food Syst* 1–12.
- 498 Whittinghill LJ, Rowe DB, Cregg BM (2013) Evaluation of Vegetable Production on Extensive Green
499 Roofs. *Agroecol Sustain Food Syst* 37:465–484.
- 500
- 501 Astee L, Kishnani N (2010) Building Integrated Agriculture: Utilising Rooftops for Sustainable Food
502 Crop Cultivation in Singapore. *J green Build* 5:105–113.
- 503 Cerón-Palma I, Sanyé-Mengual E, Oliver-Solà J, et al. (2012) Barriers and opportunities regarding the
504 implementation of Rooftop Eco.Greenhouses (RTEG) in Mediterranean cities of Europe. *J Urban*
505 *Technol* 19:87–103. doi: 10.1080/10630732.2012.717685
- 506 Colón J, Martínez-Blanco J, Gabarrell X, et al. (2010) Environmental assessment of home composting.
507 *Resour Conserv Recycl* 54:893–904. doi: 10.1016/j.resconrec.2010.01.008
- 508 EC-JRC (2010) International Reference Life Cycle Data System (ILCD) handbook: General guide for
509 Life Cycle Assessment - Detailed guidance. doi: 10.2788/38479
- 510 EUROSTAT (2014) Energy statistics. <http://epp.eurostat.ec.europa.eu/>.

- 511 FAO (2013) Good Agricultural Practices for Greenhouse Vegetable Crops: Principles for Mediterranean
512 Climate Areas. 636.
- 513 Goedkoop M, Heijungs R, Huijbregts M, et al. (2009) ReCiPe 2008, A life cycle impact assessment
514 method which comprises harmonised category indicators at the midpoint and the endpoint level;
515 First edition Report I: Characterisation. Ministerie van VROM, Den Haag
- 516 Grewal SS, Grewal PS (2012) Can cities become self-reliant in food? *Cities* 29:1 – 11.
- 517 Hischier R, Weidema B, Althaus H, et al. (2010) Implementation of Life Cycle Impact Assessment
518 Methods. Final report ecoinvent v2.2 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf
- 519 ISO (2006) ISO 14040: Environmental management - Life cycle assessment - Principles and framework.
520 International Organization for Standardization, Geneva
- 521 ISO (2008) ISO 15686-5: Buildings and constructed assets - Service-life planning - Part 5: Life-cycle
522 costing.
- 523 Local action on Food (2012) A Growing Trade. A guide for community groups that want to grow and sell
524 food in our towns and cities. 80.
- 525 Marchetti L (2012) Above our heads , below the sky : a step-by- step procedure for creating and
526 managing a soilless roof community garden. Alma Mater Studiorum Università di Bologna
- 527 Mok H-F, Williamson VG, Grove JR, et al. (2013) Strawberry fields forever? Urban agriculture in
528 developed countries: a review. *Agron Sustain Dev* 24:21–43. doi: 10.1007/s13593-013-0156-7
- 529 Nielsen, Nielsen A, Weidema B, et al. (2003) LCA food data base.
- 530 Orsini F, Gasperi D, Marchetti L, et al. (2014) Exploring the production capacity of rooftop gardens
531 (RTGs) in urban agriculture: the potential impact on food and nutrition security, biodiversity and
532 other ecosystem services in the city of Bologna. *Food Secur* 6:781–792. doi: 10.1007/s12571-014-
533 0389-6
- 534 Pennisi G (2014) Sistemi fuorisuolo per l ' orticoltura in città : casi studio nella città di Bologna. Alma
535 Mater Studiorum Università di Bologna
- 536 PRé Consultants (2011) SimaPro software version 7.3.3.
- 537 Sanjuan-Delmás D, Petit-Boix A, Gasol CM, et al. (2014) Environmental assessment of drinking water
538 transport and distribution network use phase for small to medium-sized municipalities in Spain. *J*
539 *Clean Prod.* doi: 10.1016/j.jclepro.2014.09.042
- 540 Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, et al. (2015a) Integrating horticulture into cities: A
541 guide for assessing the implementation potential of Rooftop Greenhouses (RTGs) in industrial and
542 logistics parks. *J. Urban Technol.* (online):
- 543 Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, et al. (2013) Environmental analysis of the logistics of
544 agricultural products from roof top greenhouses in Mediterranean urban areas. *J Sci Food Agric*
545 93:100–109. doi: 10.1002/jsfa.5736
- 546 Sanyé-Mengual E, Oliver-Solà J, Montero JI, Rieradevall J (2015b) An environmental and economic life
547 cycle assessment of Rooftop Greenhouse (RTG) implementation in Barcelona, Spain. Assessing
548 new forms of urban agriculture from the greenhouse structure to the final product level. *Int J Life*
549 *Cycle Assess.* doi: 10.1007/s11367-014-0836-9

- 550 Specht K, Siebert R, Hartmann I, et al. (2014) Urban agriculture of the future: an overview of
551 sustainability aspects of food production in and on buildings. *Agric Human Values* 31:33–51. doi:
552 10.1007/s10460-013-9448-4
- 553 Swiss Center for Life Cycle Inventories (2010) Ecoinvent Data v2.2.
- 554 Thomaier S, Specht K, Henckel D, et al. (2015) Farming in and on urban buildings: Present practice and
555 specific novelties of Zero-Acreage Farming (ZFarming). *Renew Agric Food Syst* 30:43–54. doi:
556 10.1017/S1742170514000143
- 557 Whittinghill LJ, Rowe DB, Cregg BM (2013) Evaluation of Vegetable Production on Extensive Green
558 Roofs. *Agroecol Sustain Food Syst* 37:465–484. doi: 10.1080/21683565.2012.756847
- 559

560 **TABLE CAPTIONS**

561 **Table 1.** Life cycle inventory data of the cultivation systems and crop inputs for substrate, modified NFT
562 and floating, for 1 m² and a lifespan of 1 year. Crop inputs are defined per year, crop or day, depending
563 on cultivation systems. Water and electricity consumption for irrigations is shown per day since crop
564 cycles are different and water demand depends on crop.

565 **Table 2.** Environmental and economic indicators for lettuce crops (substrate, NFT and floating) and
566 substrate production. Results correspond to the functional unit of 1 kg of product per crop period.
567 Indicators are Global Warming (GW, kg CO₂ eq), Water depletion (WD, m³), Cumulative Energy
568 Demand (CED, MJ), Human Toxicity (HT, kg 1,4-DB eq.) and Total cost (TC, €).

569

570 **FIGURE CAPTIONS**

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

575 **Figure 2.** Environmental and economic burdens of substrate, NFT and floating production for leafy
576 vegetables: lettuce. The indicators used are Global Warming (GW, kg CO₂ eq), Water depletion (WD,
577 m³), Cumulative Energy Demand (CED, MJ), Human Toxicity (HT, kg 1,4-DB eq.) and Total cost (TC,
578 €).

579 **Figure 3.** Environmental and economic burdens of substrate production for leafy and fruit vegetables.
580 The indicators used are Global Warming (GW, kg CO₂ eq), Water depletion (WD, m³), Cumulative
581 Energy Demand (CED, MJ), Human Toxicity (HT, kg 1,4-DB eq.) and Total cost (TC, €).

582 **Table 1.** Life cycle inventory data of the cultivation systems and crop inputs for modified NFT, floating and substrate, for 1 m² and a lifespan of 1 year. Crop inputs are
 583 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
 584 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
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

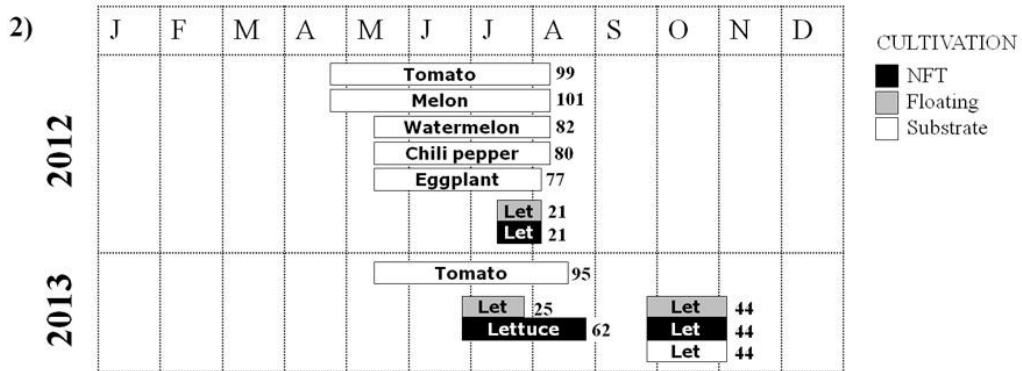
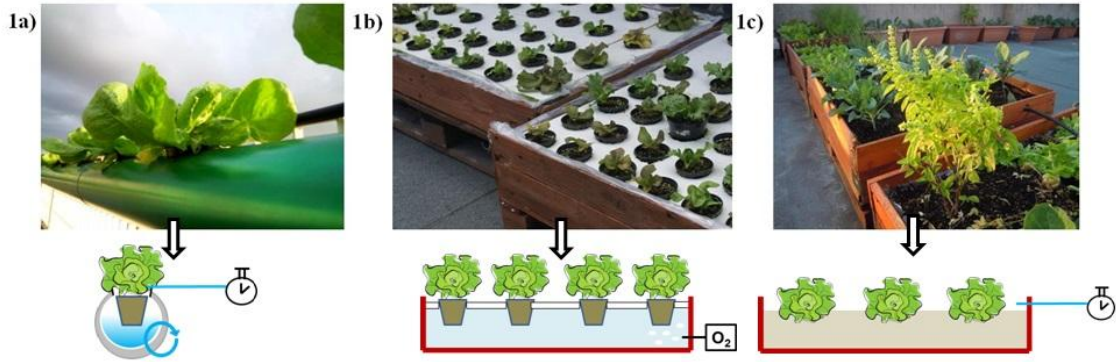
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586 **Table 2.** Environmental and economic indicators for modified NFT, floating and substrate production.
 587 Results correspond to the functional unit of 1 kg of product per crop period. Indicators are Global
 588 Warming (GW, kg CO₂ eq), Water depletion (WD, m³), Cumulative Energy Demand (CED, MJ), Human
 589 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

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591 Figure 1:

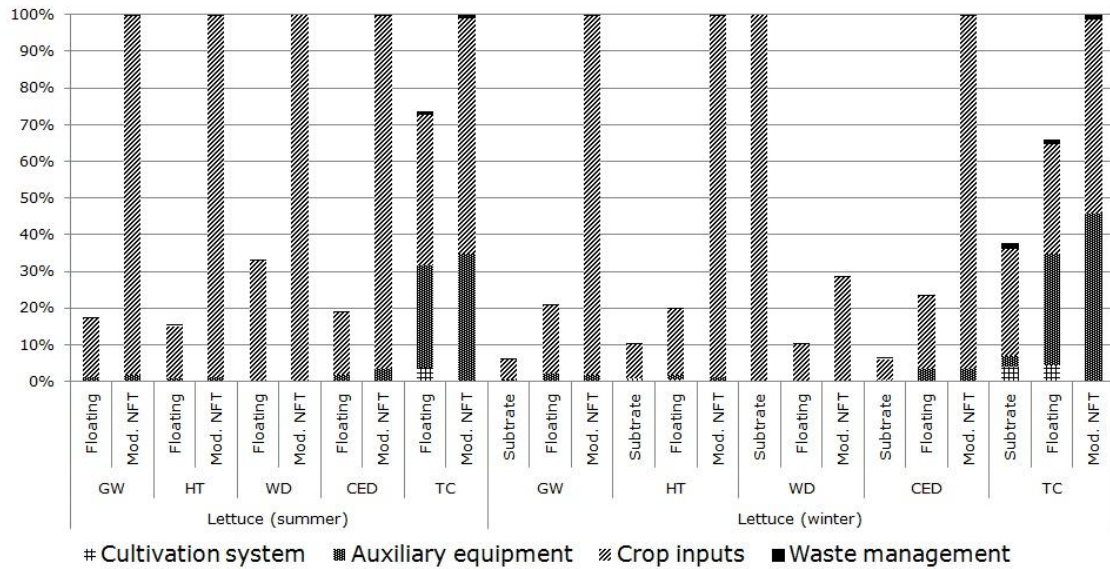


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594 Figure 2:

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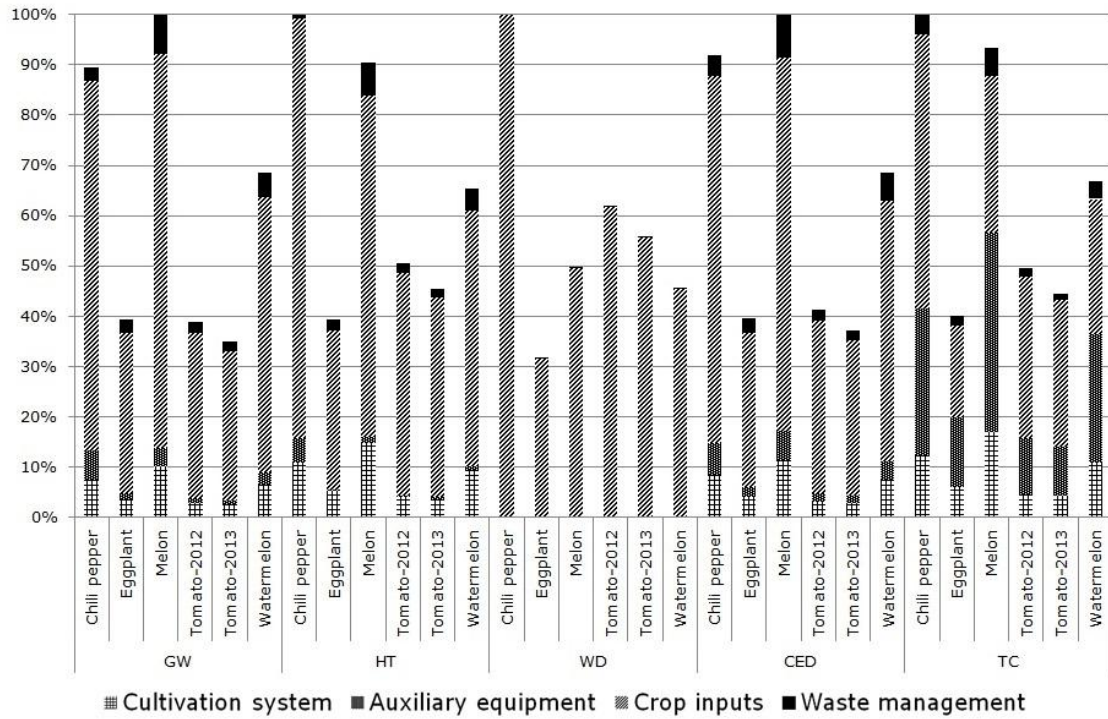
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602 Figure 3:

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