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Applying nutrient dynamics to adjust the nutrient-water balance in hydroponic crops. A case study with open hydroponic tomato crops from Barcelona

David Sanjuan-Delmás[a,b,*], Alejandro Josa[c], Pere Muñoz[d], Santiago Gassó[e], Joan Rieradevall[a,f], Xavier Gabarrell[a,f]

[a] Sostenipra Research Group (SGR 01412), Institute of Environmental Sciences and Technology (MDM-2015-0552), Z Building, Universitat Autònoma de Barcelona (UAB), Campus UAB, 08193, Bellaterra, Barcelona, Spain

[b] Ghent University, Faculty of Bioscience Engineering, Department of Green Chemistry and Technology, Sustainable Systems Engineering Group (STEN), Coupure Links 653, Blok B – 5th floor. Ghent, Belgium

[c] Department of Civil and Environmental Engineering (DECA), School of Civil Engineering (Escola de Camins), Universitat Politècnica de Catalunya, UPC, Jordi Girona 1-3, 08034, Barcelona, Spain

[d] Department of Chemical, Biological and Environmental Engineering, School of Engineering, Building Q, Universitat Autònoma de Barcelona (UAB), 08193 Bellaterra, Barcelona, Spain

[e] Group of Construction Research and Innovation (GRIC), Universitat Politècnica de Catalunya, UPC, Colom 11, Building TR5, 08222, Terrassa, Barcelona, Spain

[f] Department of Chemical, Biological and Environmental Engineering, (Catalan Biotechnology Reference Network -XRB-), Universitat Autònoma de Barcelona (UAB), Campus UAB, 08193, Bellaterra, Barcelona, Spain

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ABSTRACT

Background: Global food production systems generate impacts such as eutrophication, caused by nutrient run-off from agricultural exploitations and exacerbated by climate change. Hydroponic cultivation methods are common in Mediterranean areas, although there is a gap in the literature with regard to their study. This study aims to fill that gap, by assessing nutrient flows in hydroponic crops.

Results: The results showed that most of the nutrients were drained with the leachates (51% on average), a figure which could be lower, if the nutrient supply were adjusted to the needs of the plants or if (closed hydroponic) nutrient recirculation were implemented, without compromising the nutrient uptake of the plant. Moreover, the study revealed that a significant quantity of nutrients was retained in the substrate (perlite) during the crop, reaching average values of 5% of incoming calcium, 6% of nitrogen, and 7% of phosphorus. In the case of phosphorus and calcium, a regression model is presented for the estimation of their retention in hydroponic crops.

Conclusions: Although further studies will be needed to confirm the above trends, the study makes a significant contribution to understanding the metabolism of nutrients in hydroponic crops and to finer adjustments of the nutrient balance.

1. Introduction

1.1. Nutrient and water dynamics in hydroponic crops

The current global food production system generates significant negative impacts on the environment and consumes vast amounts of resources: 70% of global water demand is consumed by agriculture (FAO, 2011), and run-off from agricultural pesticides and fertilizers is a major source of pollution that threatens to upset the ecosystem. These impacts are often caused by leaky irrigation systems, excessive water demand, and wasteful field application methods (WWF, 2017). In that context, improvements to the efficiency of agricultural systems that can reduce their environmental impacts are of paramount importance.

Within agriculture, hydroponic cropping is a common cultivation method in greenhouses or more properly a hydroponicum where plants are cultivated in an inert substrate (such as perlite or rock wool) with crop fertigation (irrigation with a nutrient solution). Previous studies have demonstrated that the most negative environmental impacts of hydroponic crops are their fertiliser amendments (Anton et al., 2005), hence the interest in their assessment to improve their environmental

* Corresponding author at: Ghent University, Coupure Links 653, Blok B – 5th floor, 9000, Ghent, Belgium.
E-mail address: David.sanjuandelmas@gmail.com (D. Sanjuan-Delmás).

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performance.

The sustainable management of fertilisers has been analysed in the literature from the perspective of nutrient efficiency. Current practice in greenhouses with hydroponic crops significantly surpasses the recommended quantities of nutrients (Thompson et al., 2007). Nutrients that are consumed and leached can easily be reduced, while maintaining or even increasing crop yields, by adjusting the flow of nutrients to the needs of the plant (Muñoz et al., 2008; Savvas and Gizas, 2002; Şirin, 2011). In fact, excessive salinity (measured in terms of electric conductivity) in the nutrient solution for crop irrigation can reduce crop yields (Adams, 2015). Likewise, a similar method of cultivation consists of the elimination of nutrient inputs and the recycling of the leachates (i.e. only recirculating the remaining nutrients) some days before harvesting (Le Bot et al., 2001; Siddiqi et al., 2008).

This study is focused on the assessment of water and nutrient flows in hydroponic crops with no recirculation of water and nutrients, i.e., open hydroponic crops; the most commonly used system in Mediterranean greenhouses (Muñoz et al., 2010). Water and nutrients are intrinsically linked in these systems, because both of them are affected by modified fertigation levels. Furthermore, these flows are also linked to the most significant environmental issues that concern greenhouses and agriculture in general: eutrophication and water scarcity (Andersen, 2006; Iglesias et al., 2006).

The nutrient dynamics or nutrient budget methodology (also known as nutrient accounting, element balance or nutrient flows) consists of balancing all the nutrient inputs and outputs of the farming system, in order to analyse the nutrient flows in the crops (Öborn et al., 2003). This methodology has been widely applied in soil-based agriculture, where implementation of the nutrient budget methodology involves several estimations, due to the complexity of the system (Khai et al., 2007; Oelofse et al., 2010). However, to the best of our knowledge, little information is available on nutrient dynamics in hydroponic systems.

Filling this research gap is of interest to obtain useful information that can help to understand the functioning of hydroponic crops and for the efficient management of fertigation. Previous studies on the issue have only considered the nutrient solution, the leachates, and the plant uptake, calculating the nutrient and water balance from these flows (Goins et al., 2004; Grewal et al., 2011). As Bugbee (2004) noted, the assumption that these three flows (nutrient solution, leachates, and uptake) include all the system inputs and outputs has not been analysed by drawing up a detailed mass balance. Bugbee (2004) showed the low recovery of some nutrients in recirculating crops: for instance, non-recovery of 70% of the nitrogen and 50% of the calcium. A comprehensive assessment must be implemented to address this problem, contemplating all the pathways that nutrients can follow.

There is a particular research gap regarding the amount of nutrient retention in the inert substrates used in hydroponic crops. For example, perlite, a material commonly used for that purpose, could retain important amounts of nutrients. More recent studies concerning rockwool have proved that the volatilization of nutrients might be a major source of nutrient loss in hydroponic crops (Hashida et al., 2013; Yoshihara et al., 2016). Nitrogen volatilization in the form of N_2O can be as high as 16% of the total nitrogen supply (Hashida et al., 2013; Yoshihara et al., 2016). Research continues to clarify these flows, even though it is beyond the scope of this study, due to the methodological complexity of their assessment.

1.2. Analysing water and nutrient flows in crops from an industrial ecology perspective: the integrated rooftop greenhouse (i-RTG)

The research conducted in this study was developed in an innovative food production system called the integrated rooftop greenhouse (i-RTG), located in the ICTA-ICP Research Centre, on the campus of the Universitat Autònoma de Barcelona (Spain). This greenhouse holds a symbiotic interface with the building, recycling water, energy, and CO_2, saving on resources, and reducing environmental and economic impacts (Fertilecity, 2016; Sanjuan-Delmás et al., 2018).

The potential industrial ecology of this system is under evaluation, to establish the extent to which it can increase food production in cities and prevent environmental impacts (Cerón-Palma et al., 2012; Pons et al., 2015; Sanyé-Mengual et al., 2013). In this context, the analysis of different flows in the system provides useful insights into the utilisation of resources for agriculture.

The main goal of this study is to analyse both the nutrient and the water flows in hydroponic crops, implementing the nutrient dynamics methodology for greenhouse crops in a Mediterranean climate. The specific objectives are, firstly, to define all the flows and stocks of water and nutrients in an open hydroponic system. Secondly, to measure the nutrient flows and their uptake in experimental tomato crops, considering three crop cycles (15.5 months in total) and using the nutrient dynamics methodology. Thirdly, to provide recommendations to improve nutrient efficiency in open hydroponic crops.

2. Materials and methods

2.1. Description of the integrated rooftop greenhouse (i-RTG)

The i-RTG is located in the south-eastern corner of the rooftop of the ICTA-ICP building (GPS coordinates: 41°29′51.1″N, 2°06′31.4″E) (Fig. 1). Regarding the symbiosis with the building, there is a rainwater harvesting system that provides water for the irrigation of crops and ornamental plants. This rainwater was periodically tested to ensure its suitability for the crop and also to measure the quantity of nutrients contained (usually insignificant). Moreover, the building holds a thermal interconnection with the greenhouse to provide heat when necessary. This interconnection arrives through two paths: the ventilation air from occupied spaces in the building (via handling units) and air heated by solar radiation rising through the double skin cavity (connected to the greenhouse). Moreover, the prior air from occupied spaces in the building also contains a higher amount of CO_2 from the user's breathing, which can be beneficial for the crop. The automatic system that regulate these exchanges was specifically designed by SIEMENS for this building, with the purpose to provide optimal thermal conditions (14–26 °C) for Mediterranean horticultural crops in closed systems. More information about this system can be found in previous literature on the topic (Nadal et al., 2017; Sanjuan-Delmás et al., 2018).

2.2. Plant materials and growth conditions

The laboratory has an area of 122.8 m^2 (Fig. 1), and the crop area is 84.34 m^2. The crop in this study included 171 tomato plants, 47 of which were on the perimeter and 124 were non-perimeter plants.

Beefsteak tomato (*Lycopersicon esculentum* var. *Arawak*) was cultivated. Seedlings grown in peat (at a local garden centre) for 4–6 weeks were transplanted into perlite bags (brand OTAVI®) in the greenhouse. Perlite was used as a substrate in bags of 40 L by volume and 1 m in length; these bags were placed in lines, each providing substrate for three plants. New bags were placed at the beginning of the first crop and maintained until the end of the third one. An open hydroponic system was used for irrigation, providing the nutrient solution to plants using drippers with 2 L/h of flow.

Cultivation started in February 2015 and ended in July 2016, excluding August 2015 when there was no activity in the building. Three cultivation phases were considered, although the third crop (affected by various diseases) was interrupted due to its critical condition.

With regard to the nutrient solution, Table 1 shows the concentration of nutrients provided to the crop over the three cultivation periods, guided by the agronomic expertise of the authors, following similar criteria explained in previous studies (Muñoz et al., 2010). The irrigation was constantly adjusted, so that the drainage remained between 30 and 40%. The electric conductivity (CE) and the pH of the nutrient

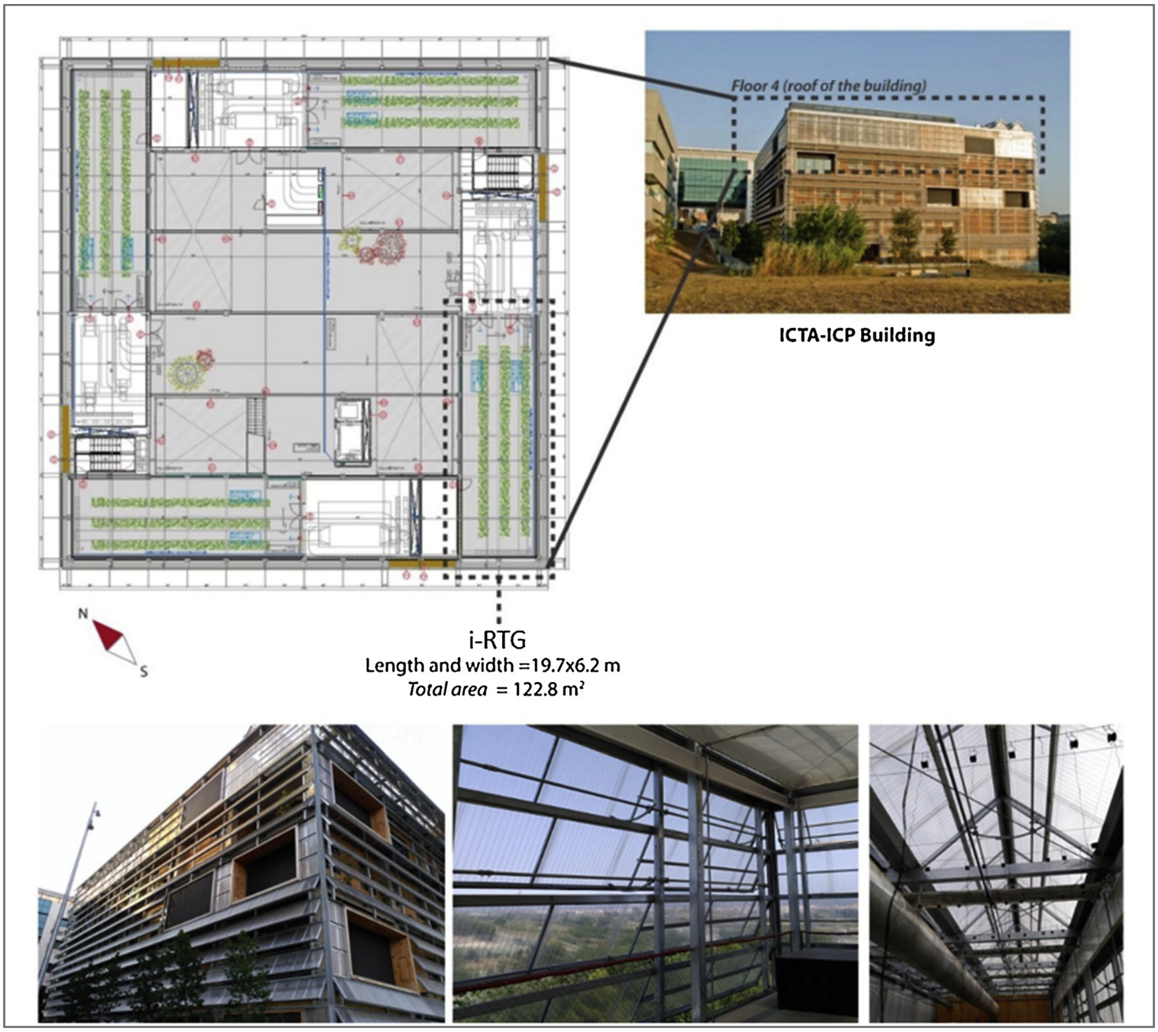

Fig. 1. Layout of the rooftop of the ICTA-ICP building and the i-RTG (top), ICTA-ICP building on the UAB Campus (bottom left), greenhouse walls (bottom centre), greenhouse roof (bottom right).

Table 1
Concentration of nutrients in the hydroponic solution supply between 10/02/2015 and 20/07/2016.

	Days (n)	Nutrient concentrations (mM)*						
		NO_{3-}	$H_2PO_4^-$	SO_4^{2-}	Cl^-	K^+	Ca^{2+}	Mg^{2+}
S1	77	10	1	1.5	2	7	3	1.5
	87	11.5	1	2	2.5	7	4	2
W	111	7	1	1.5	3	5	3	1.5
	21	7.5	1	1	3	5	3	1.25
	37	7.5	1	1	3	5	3	1.25
S2	24	8.5	1	2	2	6	3.75	1
	122	9	1	1.5	2	6	3.5	1

S1 = First summer crop 1, S2 = Second summer crop W = Winter crop, *The solution was adjusted for each crop following the recommendations of the agricultural experts and in accordance with the nutrient concentrations found in the leachates and the state of growth the crop.

solution and the leachates were measured on a daily basis, to detect any alteration in the nutrient content of each flow. The nutrient solution was adjusted when necessary according to the quantity of nutrients in the leachates.

2.3. Quantification of the nutrient flows

The following flows were considered for the evaluation of the nutrient dynamics: Nutrient solution (incoming solution for irrigation), leachates (outgoing solution, excess water drained from the substrate, fruits (crop production for consumption (tomatoes)), biomass (leaves, stem of tomato plants and roots) and perlite (crop substrate). Notice that we consider fruit and biomass different categories, although fruit is biomass, it has very different properties and destination. Whereas biomass is all the biomass that remains in the system to be disposed, fruits are the product to be consumed.

Aiming at quantifying the flows of nutrients in the crop, both the total flow (volume of nutrient solution or kg of produce) and the nutrient concentration in the flow (for instance, the ppms of N in the nutrient solution and the g of N per kg of produce) were experimentally measured.

It must be highlighted that the study of the consecutive crops was an iterative process. Although the aim was always to assess the flows of nutrients, the experience of each crop was used to improve the managing and measurements in the following. Thus, the procedures and techniques for the analyses of the nutrient concentrations were modified in the second and third crops. For the measurement of the main macronutrients (N, P, K, S, Mg, Ca), ion chromatography was used for the hydroponic solution and the leachates and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) was used for biomass, fruits and perlite. Moreover, elemental analysis was used for the measurement of carbon in the biomass, fruits and perlite as well as for nitrogen in the perlite. Finally, ICP-OES was also used during S2 to analyse some micro-nutrients (Na, Fe, Zn, Mn) in all the flows (hydroponic solution, leachates, biomass, fruits and perlite).

All the results of the sample analyses are available in the Supplementary Material. The following sections give detailed explanations of the methodology implemented for each flow and each crop.

2.4. Nutrient solution and leachates

To measure the volume of nutrient solution used in each crop (incoming water and nutrients to the system), a flow meter was used at the entrance of the irrigation head circuit. To estimate the leachates from the crop (output of nutrients and water), two water collection trays (three for crop S2) were placed under substrate bags in different parts of the crop, to collect the leachates and to measure their volume daily. These trays were strategically placed in different parts of the greenhouse and under non-perimeter plants to be as representative as possible of the crop. The value obtained for these trays was used to estimate the total volume of leachates leaving the system.

Regarding the concentration of nutrients in these flows, samples of the nutrient solution were analysed once every week, while the leachates were analysed three times every week throughout the growth of crops S1 and W. A more precise procedure was used for the third crop (S2), to increase the reliability of the quantification. A sample was collected daily for each of the flows, and a representative sample for each week was prepared, taking the proportional volume of the daily samples according to the water used for irrigation and the leachates that were generated.

As shown in Table 2, sample analyses were taken with ion chromatography, to obtain the concentrations of nitrite, nitrate, phosphate, potassium, sulfur, magnesium, and calcium for all three crops. In crop S2, additional micronutrients (sodium, iron, zinc, and manganese) were measured using Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES).

The product of the volume multiplied by the concentration of nutrients in the flow yielded the total flow of nutrients supplied and leached.

2.5. Fruits, biomass and perlite

All production from each of the three (tomato) fruit crops was weighed to obtain the total amount of produce. Two samples of tomatoes were collected for crop S1 and six for W and S2, to assess the concentration of nutrients in the produce. Each sample was prepared by collecting six representative tomatoes (average size, normal shape, and from a non-perimeter plant) from one line of plants, which were dried at 70 °C for 48 h (more if required, until weight stabilisation) and mixed. The resulting samples were analysed by ICP-OES for nitrogen, phosphorus, potassium, sulfur, magnesium, calcium, sodium, iron, zinc, and manganese (Table 2). The average nutrient concentrations for each crop from the samples analysed were considered. For each nutrient, the total quantity contained in the fruits was calculated following Eq. (1), in which *NT* is the total amount of nutrient in the tomatoes of a crop, *CT* is the concentration of nutrient in the tomatoes, *QT* is the total amount of tomatoes produced, *c* is the specific crop considered, *i* is the sample collected and *N* is the number of samples collected.

$$NT_c = \frac{\sum CT_{i,c}}{N} \bullet QT_c \qquad (1)$$

A similar methodology was implemented for biomass. During the crops, all the biomass from pruning (removal of the stems and leaves that are not part of the main stem, or that are in the lower part of the plant when all the tomatoes have been collected from such part) was weighed, as well as the remaining biomass from the plants at the end of the crop. Regarding the concentration of nutrients in the biomass, four

Table 2
Nutrient flow quantifications of the three crops (analyses conducted between February 2015 and July 2016).

		Nutrient Solution	Leachates		Production			Biomass			Perlite		Evapotranspiration		Balance
		g	g	%[1]	g	%[1]	g/kg d.s	g	%[1]	g/kg d.s[2]	g	%[1]	L	%[1]	%[3]
N	**S1**	10.549	5.366	51%	1.738	16%	23	1.571	15%	27	646	6%	–	–	90%
	W	2.825	1.097	39%	514	18%	24	1.335	47%	39	184	7%	–	–	112%
	S2	3.698	1.659	45%	1.147	31%	20	1.504	41%	32	204	6%	–	–	124%
P	**S1**	2.264	712	31%	425	19%	6	711	31%	12	139	6%	–	–	89%
	W	1.027	249	24%	131	13%	6	625	61%	18	63	6%	–	–	105%
	S2	1.303	323	25%	230	18%	4	494	38%	11	122	9%	–	–	91%
K	**S1**	24.276	13.084	54%	3.091	13%	40	2.833	12%	54	0	0%	–	–	80%
	W	8.910	4.063	46%	1.012	11%	47	2.351	26%	69	0	0%	–	–	85%
	S2	9.099	4.859	53%	1.853	20%	33	2.382	26%	59	105	1%	–	–	103%
S	**S1**	5.403	3.678	68%	1	0%	2	2.198	41%	31	0	0%	–	–	110%
	W	1.901	1.134	60%	54	3%	3	611	32%	18	0	0%	–	–	96%
	S2	2.171	1.408	65%	86	4%	2	1.176	54%	21	53	2%	–	–	127%
Mg	**S1**	2.364	1.366	58%	128	5%	2	260	11%	4	0	0%	–	–	76%
	W	1.135	613	54%	38	3%	2	299	26%	9	0	0%	–	–	85%
	S2	872	566	65%	75	9%	1	264	30%	5	44	5%	–	–	111%
Ca	**S1**	13.640	6.957	51%	90	1%	1	3.499	26%	51	472	3%	–	–	82%
	W	5.024	2.097	42%	47	1%	2	1.811	36%	53	296	6%	–	–	86%
	S2	4.890	2.477	51%	52	1%	1	2.588	53%	47	322	7%	–	–	113%
Water[4]	**S1**	82.142	28.102	34%	1.250	2%	–	318	0%	–	417	1%	50,952	62%	–
(L)	**W**	38.539	13.707	36%	350	1%	–	309	1%	–	417	1%	23,340	61%	–
	S2	41.796	18.479	44%	848	2%	–	253	1%	–	417	1%	21,195	51%	–
Carbon[5]	**S1**	–	–	–	24.909	57%	–	18.267	42%	–	364	1%	–	–	–
	W	–	–	–	7.348	39%	–	10.820	58%	–	511	3%	–	–	–
	S2	–	–	–	16.067	50%	–	15.176	48%	–	608	2%	–	–	–

[1] Percentage in relation to the incoming nutrients in the nutrient solution.
[2] Average from stem and leaves based on the weight of stems and leaves in the crop.
[3] Total balance (addition of all flows in relation to incoming nutrients), [4] Evapotranspiration was calculated by substracting the rest of the flows from the irrigation (nutrient solution). [5] The percentage refers to total fixed carbon (additions of biomass, produce and perlite). S1 = Summer crop 1, S2 = Summer crop 2, W = Winter crop, d.s. = dry sample.

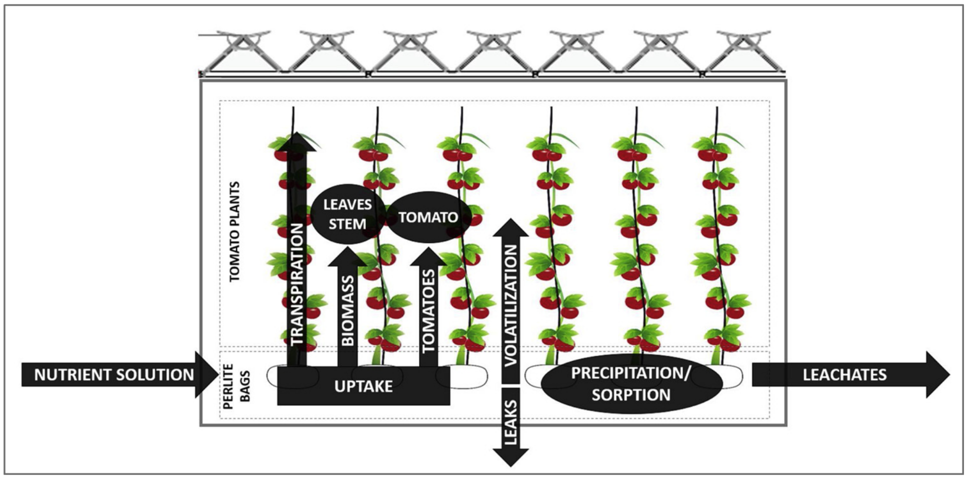

Fig. 2. Schematic of the nutrient and water flows in the crop.

representative plants (three from S2) were cut from different lines during the final phases of crop maturity (to minimize the influence on production). Leaves, stems and any remaining fruits on each plant were separated, and the leaves and steams were analysed following the same process and techniques used for the tomatoes (for the same nutrients). The nutrient flow into the tomato fruits was expressed as the average concentration of the nutrients in the samples under analysis in each crop multiplied by the total biomass of each crop.

Likewise, nutrient retention in the perlite was measured on the basis of the total amount of perlite. The weight of an (unused) dry bag was multiplied by 57 (bags in the crop), to obtain the total perlite in the crop. The concentration of the nutrients was measured at different points during the three crops, thereby yielding the accumulation of nutrients in the perlite.

Firstly, a preliminary analysis of nitrogen in a sample of perlite from S1 and a blank (unused perlite) was performed with an auto-spectrophotometer (Bran + Luebbe AutoAnalyser3). After this preliminary analysis, samples of perlite that had been used for different periods of time were analysed. At the end of the second crop (W), two perlite bags were taken for analysis and replaced by new ones. The analysis served to measure the retention of nutrients during S2 in bags that had not been used for the previous crops. Therefore, at the end of the experiment, the bags that had been removed had only been used for the first and second crops (S1, W), the replacement bags only for the last crop (S2), and the rest of the bags for the three crops (S1, W, S2). A sample was taken from each bag plus one blank, but some of the results obtained were not conclusive and a second batch of samples was collected to observe any variations between the bags. In this second batch, two samples were taken from two perlite bags used in S1 and W (four samples in total), three samples were taken from two perlite bags used for crop S2 (six in total), and 12 samples of the blank were taken from six unused perlite bags. As commented above, all the analytical results can be found in the Supplementary material.

Each bag was opened and spread on the floor, hand-mixing the perlite to form a layer of uniform thickness, in order to select the perlite samples for analysis. The layer of perlite was divided into 20 sections, to take representative samples, and approximately equal amounts were removed from each section with a spoon. The sample was then carried to the lab in a plastic jar and a similar process was conducted using a plastic tray to obtain a smaller sample for analysis. For each sample (except the blank), the roots of the plant were carefully removed to measure only the nutrients retained in the perlite, rather than the organic matter. The sample was then dried at 383 K and ground using an analytical mill.

The samples of perlite were digested in duplicate with concentrated HNO_3 in a microwave oven together with digestion blanks. The samples were then lixiviated, and the solids removed, leaving the liquid solution with the nutrients extracted from the perlite, which were analysed using ICP-OES for nitrogen, phosphorus, potassium, sulfur, magnesium, calcium, sodium, iron, zinc, and manganese.

The results of that assessment provided the variation in nutrient concentration (mg of nutrient per g of perlite) in the perlite substrate. The correlation between those values and certain key variables of the crops were assessed, looking for patterns in the accumulation of the nutrients. The variables under consideration were: nutrient concentrations in the nutrient solution and the leachates after harvesting the crop, the nutrient load of the nutrient solution and the leachates (quantity of nutrient supplied and leached), and the duration of the crop (number of days of nutrient uptake from the perlite).

The accumulation of nutrient in the perlite was obtained from the difference between the concentrations that were measured in the perlite and the total amount of perlite in the crop. For the nutrients that presented a clear pattern of accumulation, the quantity of nutrient accumulated in each crop was estimated.

Finally, an elemental analysis of all the solid samples (fruits, biomass, perlite) was performed, to identify the content of carbon, hydrogen, and nitrogen in the sample. The results from these analyses were also used to calculate the nutrient flows in the system.

3. Results and discussion

3.1. Characterisation of water and nutrient flows

All the water and nutrient flows of potential significance in the crop were identified and are represented in Fig. 2.

The water and the nutrients both followed similar paths, because the nutrients provided to the plants were dissolved in water (fertigation solution). The major flows of water and nutrients were the nutrient solution supplied to the crop, the leachates (an excess of water, estimated at be between 30 and 40% of the incoming water) and the evapotranspirated water (plant uptake released to the atmosphere). Some water and nutrients remained in the plants in the form of biomass (plants) and fruits (tomatoes). However, unlike water, there is no evapotranspiration of nutrients in a biomass, although there is some drainage and a certain percentage is volatilized, as has recently been demonstrated (Hashida et al., 2013; Yoshihara et al., 2016). Nutrients can also be adsorbed by perlite substrate or precipitated in the bags. It must be highlighted that evapotranspiration, leaks and volatilization were not experimentally measured in the crop (they were hypothesized for the quantification).

Small quantities of the water supply were lost through occasional leaks, most of which was evaporated or drained off. Finally, a relatively

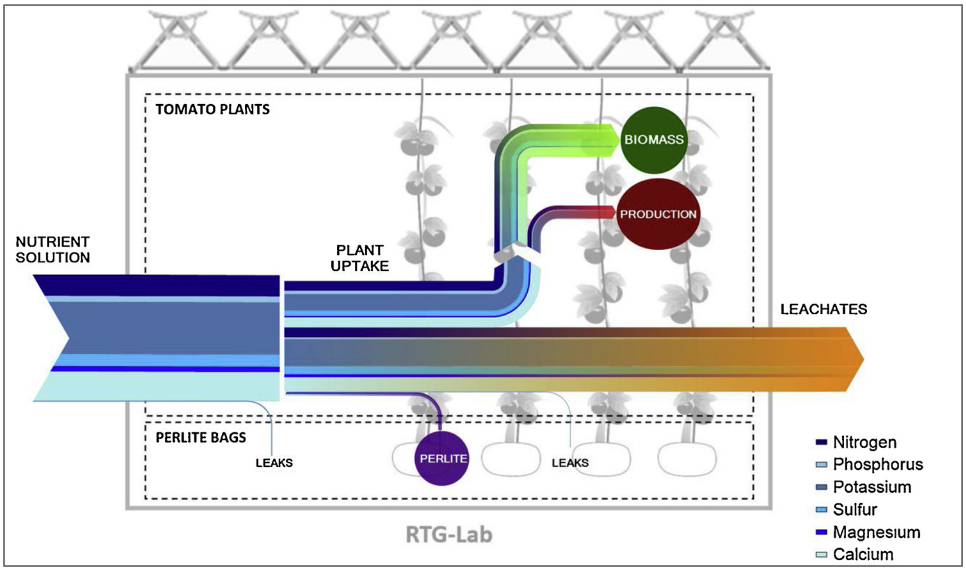

Fig. 3. Flow diagram of total nutrient flows for the open hydroponic tomato crops with perlite substrate between February 2015 and July 2016 (the width of the flows is proportional to their quantity).

small amount of water was retained in the substrate (perlite) after harvesting, which eventually evaporated or was kept in the bag for the following crop.

3.2. Nutrient dynamics for macronutrients

The quantification of the macronutrient flows (N, P, K, S, Mg and Ca) is shown in Fig. 3, considering the addition of the three crops (S1, W and S2). As can be observed, most of the nutrients were leached, representing 51% of the incoming nutrients. The second largest flow was the plant uptake for biomass and fruit production, which accounted for 37% of the nutrient supply, of which 26% went to biomass, and 11% to production. The rest of the flows represented relatively minor percentages, although the perlite retained 3% of the incoming nutrients, which can reach significant amounts for some specific nutrients. The aggregate global nutrient balance of the three crops was 94%, ranging between 85 and 111%. This balance should not surpass 100%, although due to possible estimation errors, some higher values were obtained for certain nutrients.

As stated in section 1, the nutrient dynamics methodology has not previously been implemented in open hydroponic crops. Any comparison of these results with the reference figures is complicated. However, the nutrient use efficiency of these crops was similar to the results of previous analyses of hydroponic crops and their nutrient uptake (Kläring, 2001). These results show a quantification of the main nutrient pathways and provide an initial approach to these trends that will be analysed in future research. For instance, a relatively small but significant quantity of nutrient was retained in the substrate (perlite), which will be discussed below.

Regarding the balance for each of the macronutrients under analysis, individual diagrams are shown in Fig. 4 aggregating the results for the three crops, and the detailed results for each of the crops are shown in Table 3.

Summer crops showed higher amounts of nutrient, both supplied and leached, due to the greater need for irrigation, because of the higher temperatures and radiation during this season. However, the efficiency of nutrient use was lower in winter, if the crop yields are considered, because winter crops are much less productive. For instance, crops S1 and S2 used 1.75 and 1.16 g of phosphorus per kg of tomato produced, whereas crop W used 3.54 g per kg of tomato.

Optimisation of the nutrient supply would reduce emission levels and thereby environmental impacts, all the more so as the use of fertilisers has been identified as the major environmental issue in relation to greenhouses (Montero et al., 2011). Indeed, the runoff of nitrogen and phosphorus from agriculture leachates is a major global concern (Andersen, 2006). However, over adjustment of the nutrient solution would increase the risk of nutritional deficiencies and generate agricultural problems. Moreover, the nutrient solution is the result of a combination of the different nutrients that must keep certain proportions and that are usually added in the form of salts, providing not only one but various specific nutrients. Thus, it is difficult to adjust the nutrient input to the exact quantity that is required. Despite these limitations, periodic measurements should be conducted during hydroponic cultivation, to optimize the nutrient solution and to reduce nutrient leaching.

The nutrients contained in the biomass and the fruits varied, depending on the nutrient and the crop. A significant part of the nitrogen, phosphorus, and potassium (between 14 and 20%) was consumed by the fruits (produce). In absolute terms, these quantities depend on the amount of crop production; higher for summer crops (especially for S1) than for winter ones. In contrast, the amount of nutrients in the (leaves and stem of the plant) biomass was similar for the three crop cycles, but lower percentages of the nutrients were supplied to S1, because of the higher irrigation required for that crop cycle. The higher irrigation in S1 was due to higher temperatures and solar radiation that summer, which increased the water demand (and likewise the productivity) of the crop. The nutrients in the biomass of the crop were higher than in the fruits (production) and represented the second largest flow for all the macronutrients. Thus, optimising the nutrient solution and maximising the solar radiation available to the crop can help to reduce the development of the stems and leaves of the plant. These two measures can help to restrain the growth of biomass and to improve the productivity of the crop, because less biomass will consume less resources, implying increased availability for the fruits.

Table 2 shows the concentration of nutrients in the produce and the biomass from the crops, to provide reference values for future studies. Comparison with previous data is difficult, due to the scarcity of scientific studies with similar data. The data tells us that the tomatoes had higher concentrations of nitrogen and potassium, while the biomass had significant concentrations of calcium and sulfur.

With respect to the retention of nutrients in the (perlite) substrate, the results showed that significant amounts of nitrogen, phosphorus, and calcium were retained in the perlite after cropping: approximately 5–7% of all nutrients that were supplied. That level of retention is

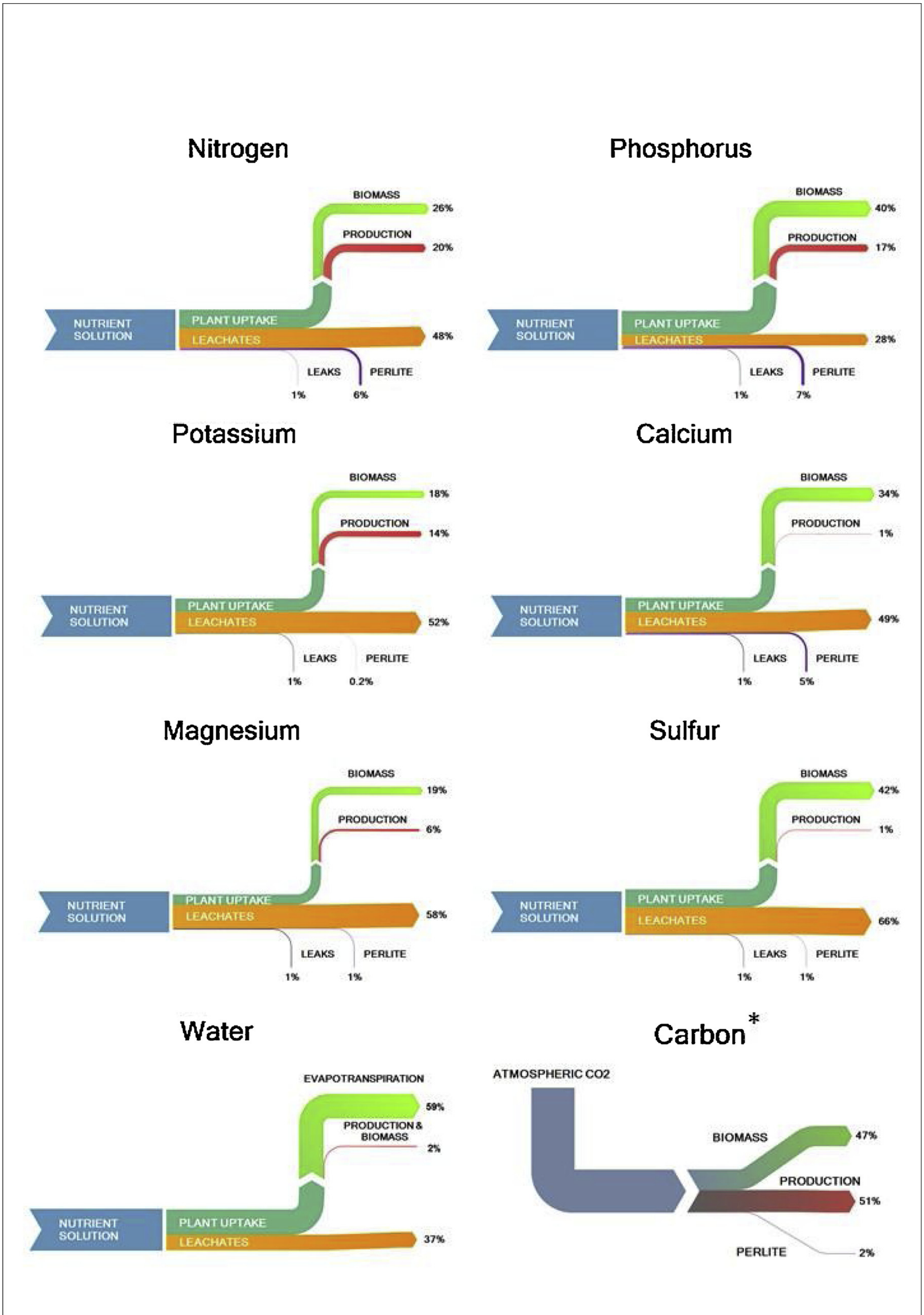

Fig. 4. Macronutrient flows aggregating the three crops (tests conducted between February 2015 and July 2016). *Atmospheric fixed carbon levels were estimated from the sum of the fixed carbon in the biomass, the produce, and the perlite.

Table 3
Flows of micronutrients in the third crop (S2) and water and carbon flows.

	Nutrient solution	Leachates		Biomass		Production		Perlite		Balance
	g	g	%[1]	g	%[1]	g	%[1]	g	%[1]	%[2]
Na	592.4	541.1	91%	61.8	10%	18	3%	68.1	11%	116%
Fe	30.3	19.0	63%	7.1	24%	0.3	1%	248.1	819%	906%
Zn	19.0	6.5	34%	1.6	9%	0.1	0%	23.1	121%	165%
Mn	12.5	0.4	3%	7	56%	0.1	1%	6.6	53%	113%

[1] Percentage in relation to the incoming nutrients in the nutrient solution.
[2] Total balance (addition of all the flows in relation with the incoming nutrients).

notable, especially as it had not previously been considered when assessing the efficiency of the hydroponic crop. Future studies implementing nutrient dynamics should factor approximate retention rates into the flow of nutrients, in order to adjust the overall balance of the different elements. These results are further analysed in section 3.4.

As can be observed, most of the nutrients remain unbalanced with percentages that are either higher or lower than 100%. However, these balances are better adjusted than others from the previous literature, which ranged between 50 and 85% of the total (Bugbee, 2004). Although these deviations might be due to the inherently limited accuracy of experimental measurements, some factors affecting these balances should be assessed in future studies. For instance, the volatilization of nutrients was proven to represent a significant percentage of the nitrogen supply (discussed above), although its investigation is beyond the scope of this study. Moreover, contamination from other sources might influence the results, such as the application of phytosanitary products (2.4 kg of wettable sulfur were applied during the three crops), which might help to explain the high percentage of the sulfur balance. However, these issues are also outside the scope of this study that limits itself to a preliminary description of the metabolism of nutrients in hydroponic crops.

The results for water flows are coherent with the water management for the crops, designed to maintain drainage at between 30 and 40%. The evapotranspiration rates, which were calculated by subtracting all the outflows to the irrigation, accounted for between 51 and 62% of the total. Although water is the main content of the fruit (production) and biomass (between 90 and 96%), their moisture content represented less than 2% of the total. One possible measure to reduce water consumption would be to adjust the irrigation to keep it closer to 30%. However, if temperatures abruptly increase from one day to another, as often happens in spring and autumn, there may be little or no time to adjust the irrigation, leading to different drainage patterns and even lost production. For instance, if the drainage drops during pollination, it can inhibit fruit formation. Similarly, if it drops during the early formation of the fruits, it can prompt blossoming, that renders the product unfit for human consumption.

Finally, the fixed carbon balance in the crop was analysed, given its relevance for climate change mitigation. The results for all the three crops showed that 44 kg were fixed in the biomass and 48 kg in the production, giving a total of more than 90 kg of biogenic carbon. The fixed carbon in the fruits (production) will return to the atmosphere in a relatively short period following consumption. Regarding the biomass, its further use as a by-product might maintain the carbon fixed during a longer period. It might for instance, be used to generate biochar that provides renewable energy and soil amendments (Llorach-Massana et al., 2017).

3.3. Micronutrient balance

The nutrient dynamics were also studied for some micronutrients (Na, Fe, Zn and Mn) for the third crop (S2). The results (Table 3) showed that the final balance was higher than 100% for all the micronutrients, indicating a greater quantity of these elements in the outflows than in the incoming solution. As discussed in the previous literature (Bugbee, 2004), these results are typical in hydroponic systems and can be due to the contamination of the fertigation solution by elements from the irrigation system, such as plastic pipes (Zn) and pumps (Fe). Their influence might explain most of the micronutrient results, except for Fe, the outflows of which were 9 times the inflow. Although a significant part of the nutrients was retained in the perlite, no clear patterns of retention were found for micronutrients (discussed in section 3.4). Between 35 and 90% of the sodium, iron, and zinc drained off and a significant part was retained in the biomass, especially in the case of manganese (56%). Balancing the micronutrients is difficult because of the small quantities carried in the flows that can also vary significantly, due to contamination, pointing to a need for more accurate measurement techniques.

4. Nutrient retention in perlite

As explained in the methodology (section 2.3.2.), the nutrient concentrations retained in the perlite substrate used for the crops were measured over different periods of time. The bags of substrate were collected after harvesting the second crop (perlite samples from 333 day-old substrate used for crops S1 and W) and after harvesting the third crop (perlite samples from 466-day old substrate used for crops S1, W and S2; and perlite samples from 133-day old substrate only used for crop S2). Thus, three points with different concentrations of nutrients were obtained (plus the blank) and possible correlations with different variables were assessed. Only the retention throughout the third crop was explicitly assessed replacing two bags at the beginning of the crop. As observed in Table 3, only the retention of the nutrients that showed a clear pattern and accounted for significant percentages were estimated in crops S1 and W.

The results showed that significant amounts of phosphorus and calcium were retained in the perlite and this retention was directly related to the duration of the period in which the perlite was used. The variable that provided a higher coefficient of determination (R^2) was the number of days in which each sample had formed the crop substrate. Phosphorus accumulation in the perlite followed a linear regression model (1) ($R^2 = 0.98$), while calcium followed a regression model (2) ($R^2 = 0.90$).

$$P = 0.003 \text{ [g of P retained/day]} \cdot N \text{ days} \quad (1)$$

$$Ca = 0.0068 \text{ [g of Ca retained/day]} \cdot N \text{ days} + 0.7803 \quad (2)$$

Nitrogen also showed substantial accumulation in the perlite, representing 6% of the nitrogen supplied for both the first crop (when only nitrogen was measured after harvesting) and the third crop, which might suggest that the perlite always retained roughly the same amount of N (around 0.1% of the dry substrate). However, the perlite used during S1 and W showed no retention, probably because the measurement threshold of the analysis was 0.1% and the retention in the sample was slightly below that value.

Retention of both magnesium and sulfur showed a linear correlation when compared with the concentration of those nutrients in the nutrient solution (for magnesium) and in the leachates (for sulfur) after harvesting. In other words, the higher the nutrient concentration, the higher its retention in the perlite. In the case of magnesium, around 0.22 mg/g was retained by the perlite or 44 g in total (5% of the Mg supplied) during the third crop. In the case of sulfur, 0.26 mg/g was retained in the perlite, amounting to a total of 53 g (only 2% of the supply to crop S). A problem with these correlations in the scatter plot for both nutrients is that it only includes three points (including the blank), because two of the samples had the same concentrations (were collected at the same point in time) and both appeared very close to each other in the scatter plot. Thus, the trending line is of low reliability and the tendency observed in the graph cannot be confirmed.

The overall percentage of potassium in relation to the total supply was only 1%, even though a relatively high quantity was retained during the third crop (0.51 mg/g of perlite, 105 g in total). Moreover, there was no correlation between those concentrations and the variables with which they were compared.

Finally, the concentration of micronutrients in the perlite was also measured, but the results could only be contrasted with the duration of the crops, because there were no micronutrients in the nutrient dynamics of S1 and W, and thus the nutrient load and its concentration after harvesting the crop could not be correlated. Table 3 shows no clear correlation with crop lifetime, even though the concentration of certain micronutrients in the perlite substrate increased during the growth of crop S2,. However, the solution included small quantities of these nutrients, suggesting that their presence in the flows was due to contamination, as discussed above.

5. Conclusions

An attempt to fill a gap in the previous literature has prompted this study of the nutrient dynamics of hydroponic crops, opening new and promising lines of research in the field. The study has quantified the nutrient flows in open hydroponic crops, representing an initial comprehensive attempt to close the nutrient balance of these systems and to shed new light on the matter.

Optimising the use of nutrients in hydroponic crops is key, since fertiliser consumption has become one of the most significant environmental issues related to greenhouses. The study shows that, on average, 51% of nutrients are leached, which might be reduced or recirculated (closed hydroponic systems). The same happened to the water, which could be adjusted to approach 30% of drainage, improving the efficiency of water use. However, any additional reduction of the nutrient and water supply has its limits and any over adjustment might lead to agronomic problems and loss of produce.

In this study, it has been demonstrated that significant amounts of nutrients remain precipitated within the perlite (substrate) after cropping, representing between 3 and 7% of the incoming nitrogen, phosphorus, and calcium. This finding is significant because it has not been considered in previous studies, which have measured recovery by considering only the nutrient supply (nutrient solution), the leachates, and the plant uptake. Although the results for the retention of nitrogen, magnesium, and sulfur showed clear trends, further analyses are needed to verify the patterns that have been observed. The nitrogen content of perlite samples used as crop substrate over different durations should, for instance, be analysed by a measurement technique of greater accuracy with a measurement threshold lower than 0.1%, as no pattern of accumulation was found (one of the samples registered no concentration, probably due to the instrumental limitations of the measurement technique). Specific tests to determine magnesium and sulfur content should be conducted, by allowing different concentrations of those nutrients to precipitate in the perlite and by observing the retention patterns. Moreover, other substrates used in hydroponic crops should be assessed, such as rockwool and coir.

Nutrient retention in the perlite implies an overall loss of nutrients when the perlite bag is dumped as a solid waste at the end of its useful life. From an industrial ecology perspective, the use of this perlite as a soil amendment might recover some of the otherwise lost nutrients and would represent a more sustainable management practice of the waste from hydroponically grown crops.

The analysis of the micronutrients showed how their adjustment, to fine-tune the balances might be complicated, due to the small quantities used in the nutrient solution (for crop S2, 30 g of iron were supplied, vs. 3.7 kg of nitrogen), as well as the risk of contamination of the nutrient concentrations. However, the relevance of micronutrients from an environmental perspective is limited, because only small quantities are required, and the leachates hold low concentrations when compared with the higher environmental impacts of macronutrients such as nitrogen and phosphorus.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:10.1016/j.scienta.2019.108908.

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