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N_2O emissions from protected soilless crops for more precise food and urban agriculture life cycle assessments

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Abstract

Due to population growth and the subsequent increase in the demand for food, low carbon food chain production systems are a necessity to reduce the effects on climate change as much as possible. Urban agriculture is of great interest because of its potential in reducing the indirect CO_2 emissions of a city's food supply by reducing transportation distances, the packaging required and the food losses that occur during transportation. However, intensive urban agriculture production, which often relies on the use of soilless substrates, requires synthetic fertilizers rich in nitrogen, resulting in N_2O emissions. Presently, there is a lack of studies that determine the generation of N_2O from soilless crops to properly account for their global warming potential. In this study, an open chamber system was used to quantify N_2O emissions from lettuce crops with perlite bags as their substrate in a Mediterranean rooftop greenhouse located in the metropolitan area of Barcelona (Spain). N_2O generation, through nitrifying and denitrifying reactions, was limited by assuring an aerobic environment, negligible water retention, the absence of NH_3, and controlled dosage of NO_3- in the most favorable pH conditions for plant assimilation. The emission factor (EF) measured for the soilless lettuce crop (0.0072 - 0.0085 kg N_2O^{-1} per kg N^{-1}) was half the EF of the IPCC method (0.0125 kg N_2O^{-1} per kg N^{-1}) for soil crops, which is commonly used in life cycle assessment (LCA) studies to approximate direct N_2O emissions, for lack of a better method. Using a more appropriate EF for an LCA study of a tomato crop grown under similar conditions to those used to generate the EF resulted in a 7.5% reduction (0.06 kg CO_2 eq. per kilogram of tomato production) in total global warming potential. This study shows that soilless crops reduce N_2O emissions when compared to conventional crops, making urban agriculture an attractive practice for reducing GHG emissions. The results highlight the need to determine a standard method for determining an EF applicable to soilless protected crops, which, based on the parameters described here, such as the type of substrate, fertilizers and irrigation system, would allow for a more accurate environmental evaluation of soilless conventional and urban crops.

Keywords

N_2O emissions; Soilless crops; Low carbon food chain; Nitrogen balance; Urban agriculture; Carbon footprint; roof top greenhouses.

Highlights

- N balance from an urban soilless lettuce crop was performed.
- The N_2O emission factor for an urban soilless lettuce crop was determined.
- Soilless systems could reduce GHG emissions from urban agriculture crops.
- Further research is needed to generate precise, agricultural N_2O emissions factors.

1. Introduction

High nitrogen (N) demand for food production due to an ever-growing population has resulted in an alteration of the natural N cycle in the air, on land and in the water on both regional and global levels (Galloway et al., 2004). Direct N_2O emissions from the agricultural sector represented 6% of total European greenhouse gas (GHG) emissions in 2012. The atmospheric concentration of N_2O is of great concern because N_2O is a GHG with a global warming potential (GWP) 298 times that of CO_2 for a 100-year time span (IPCC, 2013) and is also responsible for stratospheric ozone depletion (IPCC, 2014a, 2014b). By 2050, global food production is estimated to rise by 30% (Alexandratos and Bruinsma, 2012), as a consequence of an increase in the global population to 9.6 billion humans by the same year (UN, 2012). Moreover, 70% of the global population will be concentrated in cities (UN, 2012), requiring more energy for food transportation and packaging and resulting in further GHG emissions. Finding more sustainable ways of producing food is imperative, especially for urban areas. One way to do this is to look for agricultural systems that produce fewer N_2O emissions to reduce GHG emissions from worldwide feeding systems (Maraseni and Qu, 2016).

Urban agriculture (UA) is a potential solution to reducing the carbon footprint of urban areas (Mok et al., 2013) because it reduces food transportation distances, packaging and food loss. Rooftop greenhouses (RTGs) are a specific type of UA consisting of a greenhouse on the roof of buildings. RTGs are of great interest due to their potential to reduce the environmental impact and costs of food production, while creating jobs in in cities (Cerón-Palma et al., 2012). Sanyé-Mengual et al. (2015) have analyzed the environmental performance of RTGs in comparison with conventional crop production using a cradle-to-grave, cradle-to-gate and cradle-to-consumer approach. The study's results suggest that producing tomatoes in a RTG in a *soilless system* can result in fewer GHG emissions than conventional tomato production, if the annual production rate reaches at least 24 kg m^{-2}. For lack of a more appropriate N_2O emission factor (EF) for soilless crops, the Sanyé-Mengual et al. (2015) study used the IPCC EF to quantify N_2O emissions from the N fertilizers supplied. However, the IPCC method used (IPCC, 2006) is based on data generated from *soil-based crops* and does not take into consideration the different substrate and fertilizer reduction of soilless crops, as well as solar radiation,

temperature, humidity and other factors that could significantly influence the EF. Consequently, the GHG emissions may not be correctly calculated.

Similar to the Sanyé-Mengual et al. (2015) study, other life cycle assessment (LCA) studies that attempt to evaluate the environmental performance of soilless crops have the same handicap due to a lack of more appropriate EFs. For example, three soilless tomato crops grown in Spain, Hungary and The Netherlands were evaluated with LCA methodology in the European project EUPHOROS (Montero et al., 2011) using the same IPCC soil-based EF for all locations, without taking into account how the soil-less substrate and the differing climate conditions could affect the GHG emissions during the growth phase. Similarly, Torrellas et al. (2012) assessed how various degrees of fertilization affect the LCA of a soilless tomato crop grown in Southern Spain. Even though they used the IPCC EF, the study concluded that one of the most important factors in curtailing the carbon footprint of the fruit is the reduction of direct emissions to air caused by N fertilizers, further evidencing the need for a more appropriate N_2O EF for soilless crops. Payen et al. (2015) reached comparable conclusions in their cradle-to-market analysis of local versus imported tomatoes grown with soilless systems in France. They concluded that the environmental assessment is especially sensative to both the EF used to determine the direct N_2O emissions and the transportation requirements of the fruit.

In soil-based crops, emissions of N_2O result from nitrification and denitrification reactions as shown in Fig. 1a. The inert conditions of substrates used in soilless crops and their low capacity to retain water can inhibit the microbial population growth that produces N_2O emissions through nitrification, making denitrification the main mechanism (Ruser and Schulz, 2015). Consequently, applying the IPCC EF, even as a rough approximation, could significantly overestimate the N_2O emissions from soilless crops. Furthermore, in soilless crops, N fertilizers can be exclusively provided through nitrate (NO_3^-) doses via the irrigation system, as shown in Fig. 1b, thereby limiting the amount of ammonium (NH_4) present in the substrate, which could lead to N_2O via nitrification (Gianquinto et al., 2013). In addition, an optimal NO_3^- dose, as well as favorable pH conditions (between 5.5 and 6.5) to facilitate optimal plant N assimilation, should prevent the accumulation of NO_3^- in the substrate, which would otherwise lead to N_2O via denitrification (Gianquinto et al., 2013; Savvas et al., 2013). The denitrification route shown in Fig. 1b is further limited by the fact that the high porosity of the substrate results in an aerobic environment (Ruser and Schulz, 2015). In an aerobic environment, microorganisms have enough available oxygen to continue with their activity, so the denitrification process is not necessary for obtaining the required oxygen.

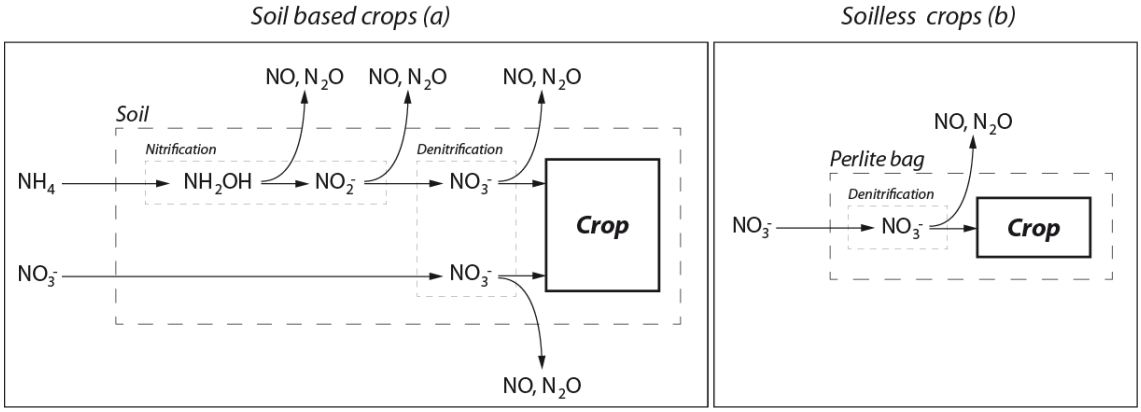


Figure 1. (a) N_2O emissions through the nitrification – coupled – denitrification process in soil based crops, adapted from Reiner Ruser and Rudolf Schulz (Ruser and Schulz, 2015)**. (b) Only the denitrification process produces N_2O emissions for soilless crops.**

There are several studies that analyze direct N_2O emission from fertilized crops, but very few that determine the EF for soilless crops (table 1). Yoshihara et al. (2014) experimentally measured an emissions factor of 0.01-0.046 kg N_2O^{-1} per kg N^{-1} for a tomato crop grown in rockwool substrate. The study examined the change in N_2O emissions response after fertilization with different concentrations of fertilizer and found that 90% of N_2O emissions occurred within the first two hours of fertilization, with a main emissions peak at the 90^{th} minute. Furthermore, they realized that halving the concentration of fertilization reduced N_2O emissions by more than half. A second study by Daum and Schenk (2013) estimated an emission of 0.004-0.016 kg N_2O^{-1} per kg N for a cucumber, closed-loop crop cultivated with rockwool substrate. The study found that the highest emissions rates are produced during fruit stem growth. In addition, root density increases N_2O emissions because high root respiration favors the growth of microorganisms in the substrate. Both studies provide a range for the N_2O EF that could be between 20% and 68% less than the EF published for soil crops (Bouwman, 1996) and accepted by the IPCC (2006), if efficient fertilization methods are used.

The two studies mentioned serve to note that the EFs can vary depending on the crop, climate conditions, soil, and the type of fertilization used and that further study is needed in order to establish a more generalized method to account for the emissions to evaluate food production systems. Moreover, Daum and Schenk (1998) describe how a variation between pH 4 and pH 7 of the nutrient solution influences N_2O emissions in cucumbers grown on a rockwool substrate. Emissions varied between 0.016 and 0.21 kg N_2O^{-1} per kg N. Other studies, based on soil culture crops, made evident the direct relation between N_2O emissions and soil temperature (Hosono et al., 2006), the type of soil used (Rochette et al., 2008), the water-filled pore space (Bateman and Baggs, 2005; Weier et al., 1993), the available carbon in soils (Weier et al., 1993), the crop season (Daum and Schenk, 2013; Dobbie et al., 1999) or the amount of rainfall (Dobbie et al., 1999).

With this study, we aim to add to this pool of knowledge by estimating the N_2O EF for a soilless crop cultivated in an RTG using perlite substrate. To meet the objective, N_2O was continuously monitored during the cultivation cycle of *Lactuca sativa* (lettuce) in an RTG located in the metropolitan area of Barcelona, Spain. A calculation of N balance was also performed for two experiments for further analysis. Additionally, we discuss how the N_2O EF can alter LCA results and the importance of standardizing an EF specifically for N_2O generation associated with soilless crops.

Table 1. Selection of papers that analyze experimentally the N_2O emissions of crops.

Main author	***Reference***	***Region***	***Soil typology***	***Crop variety***	***Protected crop***	***Emission factor*** ($kg\ N_2O^{-1}$ per $kg\ N^{-1}$)
Yoshihara et al.	(Yoshihara et al., 2014)	Japan	Rockwool	Tomato	Yes	0.01 – 0.046
D. Daum et al.	(Daum and Schenk, 1998)	Denmark	Rockwool	Cucumber	Yes	0.016 and 0.21
D. Daum et al.	(Daum and Schenk, 2013)	Denmark	Rockwool	Cucumber	Yes	0.004-0.016
Xiong et al.	(Xiong et al., 2006)	China	Soil	2 years consecutives crops: radish, baby bok choy, lettuce, second planting of baby bok choy, and finally celery	Yes	0.0039 -0.0224
Pfad et al.	(Pfab et al., 2011)	Germany	Soil	Rotation crop: Lettuce (summer) and cauliflower (winter) rotation crop	No	0.013-0.016
Rochette et al.;	(Rochette et al., 2008)	Canada	Soil	-	No	Arid zones: 0.0016 Humid zones: 0.017
Henault et al.	(Henault et al., 1998)	Northeastern of France	Soil	-	No	Chàlons: 0.0014-0.0018 Messigny: 0.0066-0.0076 Longchamp: 0.0248-0.0249
Hiroko Akiyama et al.	(Akiyama et al., 2006)	Japan	Soil	Tea and rice	No	Tea: 0.0282 ± 1.80% Rice: 0.0031 ± 0.31%
Qiaohui Liu et al.	(Liu et al., 2013)	China	Soil	Vegetables	Protected and not protected	Avg.: 0.0063±0.09%
H. Flessa et al.	(Flessa et al., 1995)	Germany	Soil	Sunflower	No	0.018
A. F. Bouwman	(Bouwman, 1996)	-	Soil	-	No	0.0125±1%*

**Emission factor from the literature used for the IPCC method*

2. Materials and Methods

2.1. Location and crop description

The experiment was carried out in an open chamber in an integrated RTG (i-RTG) with a southeast orientation, named the Agrourban Lab 1 (AU-Lab1) located in the Environmental Science and Technology Institute (ICTA) and Catalan Institute of Paleontology (ICP) building at the Universitat Autònoma de Barcelona campus near Barcelona (41°29'51.6"N; 2°06'31.9"E). This RTG is considered an i-RTG because it is built to exchange water, energy and air flow with the rest of the building to increase its efficiency and optimize resource use. A scheme of

158 the symbiosis between the building and the greenhouse can be found within the supporting
159 information.

160 The experiment to determine N_2O emissions was developed with a *Lactuca sativa* (lettuce)
161 soilless crop in a perlite substrate located on a concrete floor. The fertilizer composition and
162 concentration supplied to the crop through a drip irrigation system is provided in table 2. N was
163 exclusively provided in terms of NO_3^- to reduce the nitrification process from NH_4 as shown in
164 Fig. 1b. Once mixed with fertilizers, the irrigation water used had a pH of 6.4 and an electric
165 conductivity of 2.2 mS cm^{-1}, which provides favorable fertilizer assimilation conditions (Savvas
166 et al., 2013). The i-RTG provided the 2015 crop with an average relative humidity of 45% and a
167 temperature of 19°C during the winter and 23°C during the summer. The atmospheric N_2O
168 concentration inside the i-RTG oscillated between 200 and 500 ppb_v.

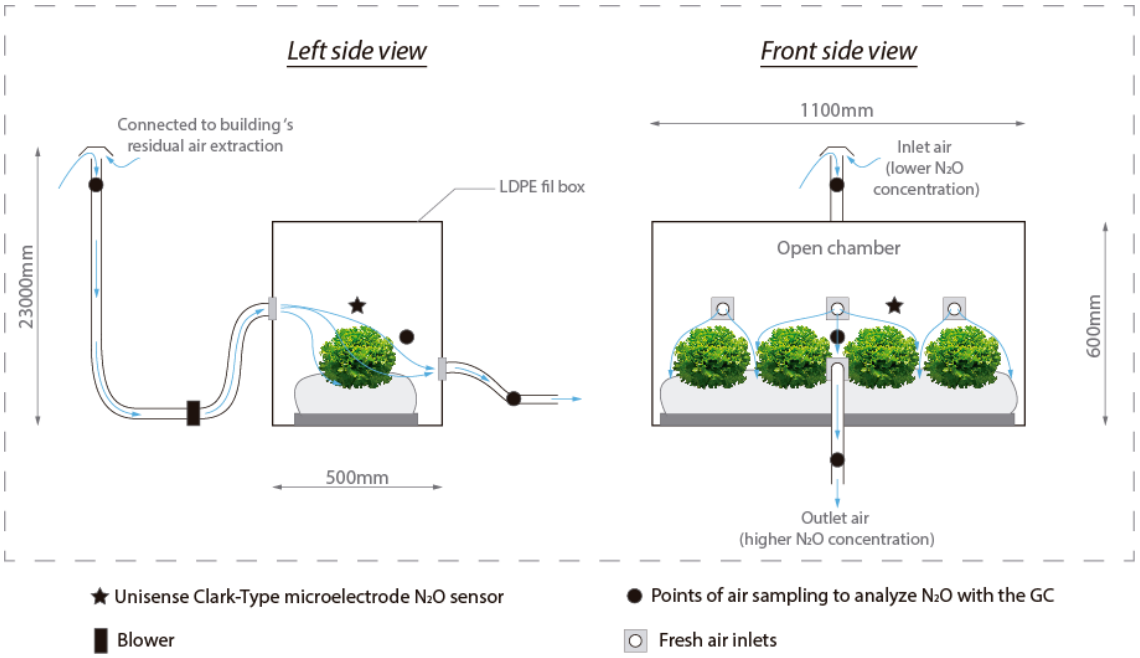
169 **Table 2. Fertilizer concentrations used for irrigation.**

	KPO_4H_2	KNO_3	K_2SO_4	$Ca(NO_3)_2$	$CaCl_2$	$CaCl_2*2H_2O$	$Mg(NO_3)_2$	Hortrilon	Sequestrene
mg/l	0.136	0.203	0.348	0.451	0.139	0.184	0.223	0.01	0.01

170

171 **2.2. Open chamber design & description**

172 Open chambers are small systems, based on a validated methodology (Garcia et al., 1990),
173 which allow for the measurement of canopy gas exchange with a certain precision. For the
174 present study, an open chamber was used to measure the potential N_2O emissions from the
175 substrate of soilless lettuce crops. The open chamber was built with LDPE (a film with low
176 reflection and high transmissivity to solar radiation) to reduce the effect of the chamber
177 structure on the temperature and humidity inside, as recommended by a previous study (Burkart
178 et al., 2007). The chamber was built with a volume of 0.33 m^3 to fit four lettuces (Fig. 2). The
179 inlet flow was forced by a blower that collected air from the building's cooling and heating air
180 extraction system and injected it into the chamber through a PVC tube with a 50 mm diameter.
181 The inlet air was between 20 and 24°C and had a CO_2 concentration of more than 400 ppm due
182 to human respiration inside the building. A potentiometer was used to adjust the power of the
183 blower and ensure a flow rate that could maintain inner chamber temperatures at the desired
184 levels.



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186 **Figure 2. Open chamber design and measurement points located inside the UA-LAB1 in**
187 **the ICTA-ICP building (Bellaterra, Spain).**

188

189 **2.3. Open chamber validation**

190 The relative humidity and temperature of the i-RTG and the open chamber followed a similar
191 evolution during day and night as shown in section 2.1 of the supporting information. However,
192 from 08/05/2015 to 12/05/2015, daily temperatures and relative humidity were 5°C and 10%
193 higher, respectively, in the open chamber than in the greenhouse. Consequently, the blower was
194 regulated to 330 m^3 h^{-1} (ensuring a renewal of the open chamber air 100 times per hour) to
195 increase air circulation and reduce these differences with respect to the i-RTG. This was
196 achieved after 13/05/2015, when differences were low enough to be considered negligible. This
197 assumption was confirmed by the similar growth rates for lettuces grown inside (10.86 ± 1.87 g
198 day^{-1}) and outside the chamber (10.51 ± 1.57 g day^{-1}). Temperature and humidity were
199 monitored inside and outside the open chamber in the proceeding experiments and never
200 presented higher differences than the ones established as insignificant (supporting information,
201 sections 2.2 and 2.3 for experiments 2 and 3, respectively).

202 **2.4. Measurements & data acquisition**

203 To achieve the objectives of the study, air samples at specific measurement points (Fig. 2),
204 inside the chamber and from the inlet and outlet air, were collected with 1-liter air bags (SKC[1] -
205 model 1.252-01) to measure N_2O concentrations. Moreover, one air sample from the greenhouse
206 was collected at the beginning of experiments 2 and 3 (table 3). Air samples were analyzed with
207 gas chromatography using an Agilent chromatograph 6890N and the Agilent HP-PLOT-Q 30 m,

[1] http://www.skcinc.com/catalog/index.php

0.53 mm, 40 µm column (hereafter referred to as GC). These samples were collected to calculate the differences in N_2O concentration between the inlet and the outlet air. The calibration line used to analyze N_2O air samples by GC had a precision of 96.8%. Therefore, an error of ± 3.2% may be assumed. Three air samples were analyzed three times to quantify the human error that can be introduced by the manual injection of the samples into the GC, which was 16 ppb_v; therefore, the maximum deviation produced by manual injection could produce an error of ± 5.3%, adding to a total potential error of ± 8.5%. To completely minimize the error, each air sample was analyzed 3 times.

Additionally, a Unisense Clark-Type microelectrode N_2O sensor was placed inside the chamber. Data from this sensor was collected with a Unisense 4 channel microsensor amplifier multimeter connected to a computer. Calibration and measurements were realized according to the method described by Marques et al. (2014). This method requires knowing the temperature of the Clark-type microelectrode, which was measured with a Campbell SCI 107 thermistor. Air samples from inside the chamber were collected and analyzed by GC to correct possible deviations of the N_2O sensor for the continuous monitoring of N_2O inside the chamber (Fig. 2). Moreover, two Campbell SCI CS215-L sensors were used to record the temperature and relative humidity inside the open chamber and inside the greenhouse (outside the chamber). To collect data from Campbell devices, a CR3000 data-logger was used. A Testo[2] hot-wire anemometer was used to quantify both inlet and outlet rate flows.

To determine leachate N concentration, samples of the leachate from the perlite bags were collected and analyzed in a chromatograph DIONEX-ICS 1000 Ion System with a Dionex Ion Pac AS9-HC RFIC Analytical 4 x 250 mm column. In addition, the volume of leachates was measured. The total N content of lettuces at the end of the crop was determined by an external laboratory. N concentrations within the perlite bag were measured according to the two-step process for analyzing different forms of N in soils as described by Bremner and Keeney (1966).

2.5. N balance

The N balance of the crop was calculated according to the following equations:

$$[1]\ N_R = N_L + N_F + N_E + N_{Ac}$$

$$[2]\ N_E = N_{outlet\ air} - N_{inlet\ air}$$

N_R represented the amount of N provided through the irrigation system (inputs); the remaining elements of the equation were related to the different outputs generated (also represented in Fig. 3): N_L was the amount of N contained within the leachates; N_F was the amount of N fixed by the crop (lettuces in this case); N_E was the emissions generated by the perlite substrate; and N_{Ac} was the amount of N that accumulated within the perlite bag.

[2] https://www.testo.com/en-US/

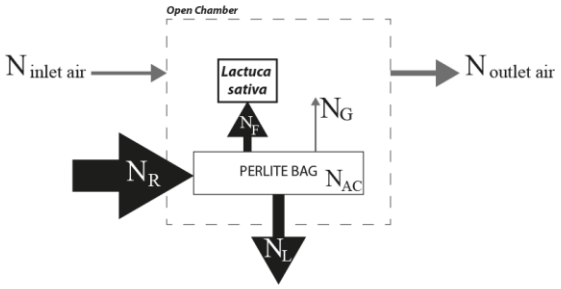

Figure 3. N flows under study. The thickness of the arrow is correlated to the amount of N within each flow.

2.6. Description of experiments

Three experiments were conducted between May 2015 and October 2015 (table 3). The first experiment served to understand and validate the open chamber as a suitable representation of the i-RTG. The N_2O emissions were measured during the second and third experiments. The latter served to validate the results of the previous experiment, and more data were gathered to be able to close the N balance. A new perlite bag was used for each experiment so as not to confound the analysis with N accumulated from a previous experiment.

252

253 **Table 3. Description of experiments**

Measurement	Units	Experiment 1	Experiment 2	Experiment 3
Date	-	04/05/2015 - 03/06/201	07/07/2015 - 14/08/2015	16/09/2015 - 15/10/2015
Objective	-	• Compare greenhouse and open chamber climate conditions. • Ensure that open chamber has no effect on lettuces growth rate.	• Measure the N input and output flows from a lettuce crop to realize the N balance. • Analyze N_2O emissions of an over fertilized crop.	• Improve the quality and repetitiveness of results from experiments 1 & 2 to realize the N balance. • Analyze N_2O emissions from a crop with a more efficient fertilization.
Greenhouse N_2O concentrations	ppmv	-	1 sample at the beginning of the experiment	1 sample at the beginning of the experiment
Greenhouse temperature & humidity	°C; %	Yes	Yes	Yes
Open Chamber temperature & humidity	°C; %	Yes	Yes	yes
N content from irrigation (chromatography)	g	-	At the beginning and end of the crop	1 sample every 4 days
N content from leachates (chromatography)	g	-	4 samples during the whole experiment	3 samples per week
Total irrigation	L	-	Yes	Yes
Open chamber inlet, inner and outlet air N_2O concentration (chromatography)	ppmv	-	3 samples per day, during 5 days at 10:00; 13:00 and 16:00	3 samples twice a week at 10:00, 13:00 and 16:00
Continuous measurements of open chamber inner N_2O concentration (N_2O microsensor)	ppmv	-	Yes	Yes
N content of lettuces cropped	g	-	Yes	Yes
N content of the perlite bag at the end of the crop	g	-	yes	Yes

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255

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3. Results and Discussion

3.1. Determining N_2O emissions

Fig. 4 shows both the average daily evolution of N_2O concentration inside the open chamber, measured continuously with the Unisense microsensor for the duration of both entire experiments (Fig. 4-a), and the chamber inlet and outlet air N_2O concentrations analyzed by GC (Fig. 4-b) for experiments 2 and 3 from 04/05/2015 to 03/06/2016 and 07/07/2015 to 14/08/2015, respectively.

It seems that N_2O generation was mostly affected by the increase in chamber temperature during the day (Fig. 4-a). Higher temperatures, which enhance the activity of microorganisms such us the thermophilic *Bacillus* sp, increase the denitrification process (Keeney et al., 1979) and consequently N_2O emissions resulting from this process (Maag and Vinther, 1996). This is best reflected by the results from experiment 2, where temperature and N_2O concentration, respectively, began to rise from 24°C and 380 ppb_v at 8:00 to 32ºC and 450 ppb at noon, when they remained stable until 16:00, at which point both temperature and concentration started decreasing back to their initial values. The dip in concentration at 14:00 further correlated the generation of emissions with temperature because during that time, the open chamber received direct shade from the greenhouse structure for approximately one hour. The correlation between temperature and N_2O emissions was not as evident for experiment 3, where the concentration peak at 12:00 did not coincide with the highest temperature. Upon closer inspection, we found that the low average concentration was a result of eight days during experiment 3 that had temperatures over 30ºC with low N_2O concentrations ranging between 205 and 212 ppb_v. The relative humidity (RH) during those days (Fig. 7 in supporting information) was lower than on any other day of the experiment (less than 50%, see Fig. 8 in supporting information). We believe that the low RH and the increased evaporation rate due to the high temperatures most likely caused the water-filled pore space (WFPS) of the perlite substrate to be low enough to inhibit nitrification (Merino et al., 2004; Pihlatie et al., 2004). Furthermore, the lettuces in experiment 3 were watered for 4 minutes every two hours instead of for 8 minutes every two hours as were the lettuces in experiment 2, thereby further reducing the amount of water in the substrate pores. For the rest of the days where RH is higher and temperatures are lower, the positive correlation between temperature and N_2O generation holds true (Fig. 8, supporting information). To summarize, it seems that temperature plays an important role in N_2O generation, but watering frequency and RH can also affect the substrate significantly and even inhibit N_2O formation.

Ambient N_2O concentrations in the i-RTG during experiments 2 and 3 were approximately 380 and 250 ppb_v, respectively, which explains the difference of 130 ppb_v between daily concentrations measured for the two experiments (Fig. 4-a). The higher ambient concentration

for experiment 2, which took place during July, could be explained by the fact that N_2O concentrations are usually higher during the warmer months in the northern hemisphere (Khalil and Rasmussen, 1983).

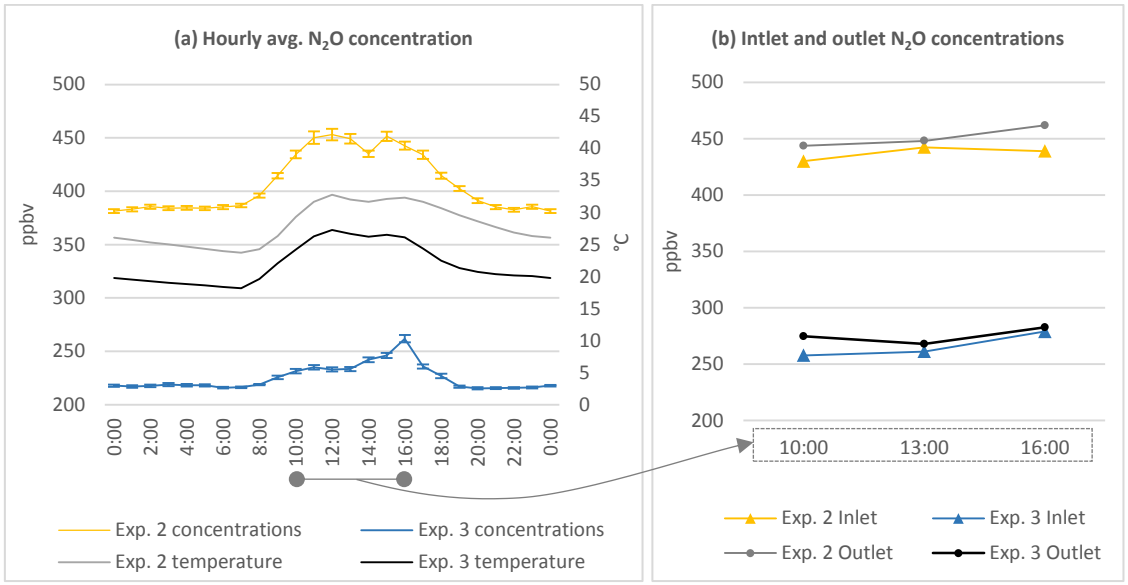

Figure 4. The average hourly N_2O concentrations in the open chamber as measured with a Unisense Microsensor (Fig. 4-a) and the N_2O concentration difference between inlet and outlet air as measured by gas chromatography (Fig. 4-b) for experiments 2 and 3.

An increase in N_2O emissions 30-120 minutes after fertilization via irrigation has been reported (Daum and Schenk, 2013). Nevertheless, we did not find a correlation between the fertilization periods and N_2O generation.

Whereas Fig. 4-a shows the hourly average N_2O concentration inside the open chamber during the entire experiment, Fig. 4-b shows the hourly average N_2O concentration, punctually measured 3 times a week during the for the duration of the experiments (table 3), of the air going into and out of the open chamber (as depicted by the circles in Fig. 2). In other words, Fig. 4-b allows an estimation of the N_2O generation inside the open chamber by calculating the difference between outlet and inlet N_2O concentrations. Total N_2O emissions were calculated considering a constant flow rate of 330 m^3 h^{-1} and the ideal gas law, resulting in $8.53 \cdot 10^{-11}$ and $6.28 \cdot 10^{-11}$ kg N_2O s^{-1} (equivalent to a total of 0.29 g and 0.15 g of N as shown in table 4) for experiments 2 and 3, respectively.

Grab air samples were taken at 10:00, 13:00 and 16:00 (Fig. 4-b) because it was considered a time frame during the day when N_2O emissions were the most significant due to more intense solar radiation and consequently higher temperatures. As can be expected, there are higher N_2O concentrations in the outlet air, reflecting N_2O generation during these hours. N_2O generation ranges from 0.014 ppmv to 0.023 ppmv and from 0.004 ppmv to 0.017 ppmv for experiments 2 and 3, respectively.

Table 4 presents the N balance for experiments 2 and 3 as calculated according to equation 1 (Fig. 3). In experiment 2, 25% of the input is unaccounted for in the output. A possible reason for this is the fact that only four samples from the leachates were collected during the entire 5-week experiment to establish an average N concentration, which was used to determine leachates N (N_L). Differences in daily volume and N content amongst the 4 samples were significant, ranging between 4.0 and 6.7 liters, with N contents between 0.09 and 0.13 g liter^{-1}. Therefore, to determine N_L based on an average of the four samples was inappropriate. Thus the N_L value of 23.59 g of N is most likely inaccurate. Consequently, for experiment 3, leachates were measured three times a week for 4 weeks to improve the N balance calculation. As a result, 95% of the input N is accounted for in the output N (table 4). The remaining 5% can be other forms of N output that are unaccounted for in this study, such as NO (Hosono et al., 2006), as well as the error introduced by the flowmeter (5%), which could overestimate the total N input.

Table 4. N balance for experiments 2 and 3. All values are given in g of N.

	2nd experiment				***3rd experiment***			
	Input		**Output**		**Input**		**Output**	
	Total	**Per 1 kg of lettuces**	**Total**	**Per 1 kg of lettuces**	**Total**	**Per 1 kg of lettuces**	**Total**	**Per 1 kg of lettuces**
Irrigation	40.08	42.07	-	-	17.88	22.38	-	-
Emissions measured	-	-	0.29 (+/- 8.5%)	0.30 (+/- 8.5%)	-	-	0.15 (+/- 8.5%)	0.19 (+/- 8.5%)
Leachate	-	-	23.59	24.76	-	-	11.80	14.77
Perlite bag	-	-	3.93	4,12	-	-	3.34	4.18
Lettuces	-	-	2.27	2.39	-	-	1.50	1.88
Total	**40.08**	**42.07**	**30.08**	**31.57**	**17.88**	**22.38**	**16.79**	**21.02**

More than half of the N supplied in experiment 2 was lost in the leachate. Thus, for experiment 3, 17.9 g of N was administered via irrigation instead of the 40.1 g of N that was used in experiment 2 (table 4). This significantly reduced N emissions from 0.29g (±8.5%) to 0.15 g (±8.5%), as well as N in the leach. In addition, the percentage of N absorbed by each kg of lettuce for experiment 3 (8.4%) was higher than for lettuces from experiment 2 (5.6%). This means that for experiment 3, the N in the fertilizers was used more efficiently. However, N per kg of lettuces is lower for experiment 3 (1.88 g, table 4) than for experiment 2 (2.39 g, table 4). A lower concentration of N fertilization reduces the final N content in lettuces, but it contributes to the absorption of other substances such as chloride, glucose or sucrose (Mccall and Willumsen, 2015), so that some nutritional compounds are substituted by others. (It is out of the scope of this research to determine if the nutritional function of these compounds is more or less important than the nutritional value of N.)

Compared with experiment 2, more N was emitted than supplied during experiment 3 (0.72% vs. 0.83%, respectivelly). The difference is insignificant when we consider the error introduced

by GC analysis, which had a ±8.5% of 250-450 N_2O ppmv. When we included the errors from the measurements, the ratio of N emitted to N supplied varied between 0.6% and -0.79% for experiment 2 and 0.76% and 0.91% for experiment 3.

The N accumulated in the perlite can potentially be emitted to the atmosphere in the form of N_2O. The emissions from the substrate at the end of its life should be accounted and attributed proportionally to each crop cultivated with the substrate. This calculation is beyond the scope of this study.

3.2. Determining the emission factor

The N_2O EFs for the soilless lettuce crop determined for experiments 2 and 3 were very similar: 0.0072 and 0.0085 kg N_2O^{-1} per kg N^{-1}, respectively. These values are roughly half the EF provided by the IPCC (0.0125 kg N_2O^{-1} per kg N^{-1}) and, on average, are lower than the EFs shown in Table 1 for rockwool based crops (0.004-0.21 kg N_2O^{-1} per kg N^{-1}). The lower EF we obtained could be explained by (1) the high porosity and low water retention potential of the perlite substrate, which provided an aerobic environment that limited denitrification reactions (Ruser and Schulz, 2015)**,** (2) the fact that nitrification reactions are limited by supplying N in the form of NO_3^- and not in the form of NH_4, as shown in Fig. 1, and (3) the use of an appropriate concentration of NO_3^- to optimize the assimilation of fertilizer as was demonstrated by experiment 3.

The results obtained are specific to perlite substrate under certain temperature, humidity and irrigation conditions. As explained by Yoshihara et al. (2014) and Daum and Schenk (2013), N_2O emissions can oscillate significantly depending on the season (affecting temperature), fertilization frequency, efficiency of fertilizer use, irrigation timing (day or night), and type of substrate. We cannot assume that the EF we obtained can be used for all soilless crops. What has been determined through this study is that further research is needed to determine an EF that can be used by LCA practitioners to evaluate the advantages of such crops. In our experiments, a more efficient use of fertilizers (using 55% less N fertilizers) reduced total N_2O emissions by 48.3%.

4. Applicability in LCA studies

To determine how the EF of soilless crops can influence LCA studies, we applied the EF determined by our analysis to an LCA study evaluating tomato crop production conducted by Sanyé-Mengual et al. (2015) in the same i-RTG where the experiments realized in this study took place. Although the Sanyé-Mengual et al. (2015) study evaluated tomato production instead of lettuce production, the EF determined for lettuce production could be applied to the

study of tomato production because both crops had the same fertilization system, climate conditions and substrate.

The system boundaries of Sanyé-Mengual et al. (2015)'s study include the assessment of the i-RTG structure, the production of tomatoes, and the distribution for commercialization of tomatoes. For the assessment of the greenhouse structure, the study accounted for the environmental impact of raw material extraction, processing and transportation, as well as the structure's maintenance and end of life. The assessment of the production of tomatoes included the fabrication, use, and end of life of the auxiliary equipment and resources required for growing the tomatoes, such as the perlite substrate, the irrigation system, water, energy, fertilizers and pesticides as well as waste management. The assessment of crop distribution encompassed the packaging production and tomato distribution up to 25 km from the greenhouse located in the city of Barcelona, Spain.

Sanyé-Mengual et al. (2015) used the IPCC EF (0.0125 kg N_2O^{-1} per kg N^-) to estimate N_2O emissions from N fertilizers and concluded that direct N_2O from the substrate was responsible for 18.05% of the total GHG emissions (0.8 kg CO_2 eq. kg $tomato^{-1}$ - see table 5). Consequently, N_2O emissions from N fertilizers represented an environmental impact higher than that of the i-RTG structure (12.0% of total GHG emissions) and more than half of the environmental impact of the production stage (26.8%, see table 5). This reduced transportation avoids 0.44 kg CO_2 eq./kg tomato in comparison with tomatoes that are produced 900 km away in southern Spain and transported to and consumed in Barcelona.

If the environmental analysis from Sanyé-Mengual et al. (2015) is calculated with the average EF determined by the present study (0.0079 kg N_2O^{-1} per kg N^{-1}), the total GWP is reduced from 0.80 to 0.75 kg CO_2 eq. kg $tomato^{-1}$ (table 5). That represents a 7.5% reduction of total GWP (1.5 kg CO_2 eq. m^{-2} $year^{-1}$ or 112.5 kg CO_2 eq. $year^{-1}$ for the entire i-RTG). It should be taken into account that in the i-RTG, N was provided in the form of NO_3^-. For crops where N is also provided in the form of NH_4, the measured EF is not applicable. Further studies are needed to quantify EF from soilless conditions when N is applied in the form of NH_4.

Between 1990 and 2012 European agricultural GHG emissions were reduce by 23%, from 600 million tons CO_2 eq. to 460 million tons (Benjamin et al., 2015). This was achieved by reducing the surplus of N fertilizers and by decreasing N losses to the hydrosphere and the lithosphere from the leachates of crops. However, the European Union still needs to look for new approaches, measures and technologies to mitigate agricultural GHG emissions (Dalgaard et al., 2014). Sanyé-Mengual et al. (2015) achieved a 33% GWP reduction in relation to conventional tomato production due to the reduction of transport distances. We show here that the environmental burden in terms of GWP is actually less when we also consider an appropriate

EF for soilless crops. In the case of the Sanyé-Mengual et al. (2015) study, the GWP could be further reduced to 40.5% of that of conventional tomato production.

Our results highlight the necessity of developing more specific EFs that can be used in LCA studies to ensure more precise analysis. For the case of urban agriculture, using an erroneous EF could significantly overestimate GHG emissions and consequently hinder proper policy making.

Table 5. GWP contributions for 1 kg of tomato production in an i-RTG according to a cradle-to-consumer study by Sanyé-Mengual et al. (2015): a comparison of results between GWP when using the IPCC and our measured EFs.

Emission factor applied			Total	i-RTG Structure	Tomato production *	Packaging	Distribution	N fertilizer direct emissions
IPCC (0.0125 kg N_2O^{-1} per kg N^-)	GWP	kg CO_2 eq.	0.80	0.10	0.22	0.49	4.74E-05	0.15
	Contribution to total GWP	%	100%	12.0%	26.84%	61.13%	0.01%	18.1%
Measured (0.0079 kg N_2O^{-1} per kg N^-)	GWP	kg CO_2 eq.	0.75	0.10	0.16	0.49	4.74E-05	0.09
	Contribution to total GWP	%	100%	12.9%	21.6%	65.5%	0.01%	12.2%

**Includes direct N_2O emissions from N fertilizers*

5. Conclusions

The experiments performed have helped determine that urban agriculture using soilless substrates has the potential to reduce GHG from feeding urban areas than what is presently estimated. This study found that by using a perlite substrate and controlled fertilization, the direct N_2O emissions from fertilization was reduced in average by up to 0.00785 kg N_2O^{-1} per kg N^{-1}, which is a 38% reduction in emissions compared with the IPCC EF (0.0125 kg N_2O^{-1} per kg N^{-1}). This result demonstrated that using the IPCC EF in soilless urban agriculture would overestimate the GWP of such food systems. In the LCA case study analyzed, there were 7.5% fewer GHG emissions (0.06 kg CO_2 eq. per kilogram of tomatoes produced) if a more appropriate EF was used.

This study does not serve to provide an EF applicable to all soilless crops, but it does show that the IPCC method presently used for LCA studies can be a significant overestimation of direct N_2O emissions and that a new method should be determined. We hope the results here help in this endeavor and shed some light on some of the parameters that influence the generation of N_2O by providing irrigation and substrate details, temperature and emission profiles, and nitrogen balance measurements and calculations.

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References

Akiyama, H., Yan, X., Yagi, K., 2006. Estimations of emission factors for fertilizer-induced direct N 2 O emissions from agricultural soils in Japan: Summary of available data. Soil Sci. Plant Nutr. 52, 774–787. doi:10.1111/j.1747-0765.2006.00097.x

Alexandratos, N., Bruinsma, J., 2012. World agriculture towards 2030/2050: the 2012 revision. Rome.

Bateman, E.J., Baggs, E.M., 2005. Contributions of nitrification and denitrification to N2O emissions from soils at different water-filled pore space. Biol. Fertil. Soils 41, 379–388. doi:10.1007/s00374-005-0858-3

Benjamin, V.D., Peter, W.H., Ingo, H., Franz, W., Thomas, F., Guna, S., Torbjorn, J., Dusan, D., Adrian, L., Thomas, F., 2015. An Economic Assessment of GHG Mitigation Policy Options for EU Agriculture, Institute for Prospective Technological Studies. doi:10.2791/180800

Bouwman, A.F., 1996. Direct emission of nitrous oxide from agricultural soils. Nutr. Cycl. Agroecosystems 46, 53–70. doi:10.1007/BF00210224

Bremner, J.M., Keeney, D.R., 1966. Determination and Isotope-Ratio Analysis of Different Forms of Nitrogen in Soils: 3. Exchangeable Ammonium, Nitrate, and Nitrite by Extraction-Distillation Methods. Soil Sci. Soc. Am. J. 30, 577. doi:10.2136/sssaj1966.03615995003000050015x

Burkart, S., Manderscheid, R., Weigel, H.-J., 2007. Design and performance of a portable gas exchange chamber system for CO2- and H2O-flux measurements in crop canopies. Environ. Exp. Bot. 61, 25–34. doi:10.1016/j.envexpbot.2007.02.007

Cerón-Palma, I., Sanyé-Mengual, E., Oliver-Solà, J., Montero, J.-I., Rieradevall, J., 2012. Barriers and Opportunities Regarding the Implementation of Rooftop Eco.Greenhouses (RTEG) in Mediterranean Cities of Europe. J. Urban Technol. 19, 87–103. doi:10.1080/10630732.2012.717685

Dalgaard, T., Hansen, B., Hasler, B., Hertel, O., Hutchings, N.J., Jacobsen, B.H., Stoumann Jensen, L., Kronvang, B., Olesen, J.E., Schjørring, J.K., Sillebak Kristensen, I., Graversgaard, M., Termansen, M., Vejre, H., 2014. Policies for agricultural nitrogen management—trends, challenges and prospects for improved efficiency in Denmark. Environ. Res. Lett. 9, 115002. doi:10.1088/1748-9326/9/11/115002

Daum, D., Schenk, M.K., 2013. Gaseous nitrogen losses from a soilless culture system in the greenhouse. Plant Soil 183, 69–78. doi:10.1007/BF02185566

Daum, D., Schenk, M.K., 1998. Influence of nutrient solution pH on N2O and N2 emissions from a soilless culture system. Plant Soil 203, 279–288. doi:10.1023/A:1004350628266

Dobbie, K.E., McTaggart, I.P., Smith, K.A., 1999. Nitrous oxide emissions from intensive agricultural systems: Variations between crops and seasons, key driving variables, and mean emission factors. J. Geophys. Res. Atmos. 104, 26891–26899. doi:10.1029/1999JD900378

Flessa, H., Dörsch, P., Beese, F., 1995. Seasonal variation of N 2 O and CH 4 fluxes in differently

493 managed arable soils in southern Germany. J. Geophys. Res. 100, 23115. doi:10.1029/95JD02270
494 Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P., Asner, G.P.,
495 Cleveland, C.C., Green, P.A., Holland, E.A., Karl, D.M., Michaels, A.F., Porter, J.H., Townsend,
496 A.R., Vosmarty, C.J., 2004. Nitrogen Cycles: Past, Present, and Future. Biogeochemistry 70, 153–
497 226. doi:10.1007/s10533-004-0370-0
498 Garcia, R.L., Norman, J.M., McDermitt, D.K., 1990. Measurements of canopy gas exchange using an
499 open chamber system. Remote Sens. Rev. 5, 141–162. doi:10.1080/02757259009532126
500 Gianquinto, G., Muñoz, P., Pardossi, A., Ramazzotti, S., Savvas, D., 2013. Chapter 10. Soil fertility and
501 plant nutrition, in: Good Agricultural Practices for Greenhouse Vegetable Crops: Principles for
502 Mediterranean Climate Areas. pp. 205–270.
503 Henault, C., Devis, X., Page, S., Justes, E., Reau, R., Germon, J.C., 1998. Nitrous oxide emissions under
504 different soil and land management conditions. Biol. Fertil. Soils 26, 199–207.
505 doi:10.1007/s003740050368
506 Hosono, T., Hosoi, N., Akiyama, H., Tsuruta, H., 2006. Measurements of N2O and NO emissions during
507 tomato cultivation using a flow-through chamber system in a glasshouse. Nutr. Cycl.
508 Agroecosystems 75, 115–134. doi:10.1007/s10705-006-9016-z
509 IPCC, 2014a. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral
510 Aspects. Contribution of Working Group II to the Fifth Assessment Report of the
511 Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J.
512 IPCC, 2014b. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects.
513 Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel
514 on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandre.
515 IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the
516 Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin,
517 G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia,. Cambridge, United
518 Kingdom and New York, NY, USA. doi::10.1017/CBO9781107415324
519 IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry
520 and Other Land Use. Chapter 11: N2O Emissions from managed soils, and CO2 emissions from
521 lime and urea application [Cecile De Klein (New Zealand), Rafael S.A. No. Hayama, Kanagawa
522 (Japan).
523 Keeney, D.R., Fillery, I.R., Marx, G.P., 1979. Effect of Temperature on the Gaseous Nitrogen Products of
524 Denitrification in a Silt Loam Soil. Soil Sci. Soc. Am. J. 43, 1124.
525 doi:10.2136/sssaj1979.03615995004300060012x
526 Khalil, M.A.K., Rasmussen, R.A., 1983. Increase and seasonal cycles of nitrous oxide in the earth's
527 atmosphere. Tellus B 35B, 161–169. doi:10.1111/j.1600-0889.1983.tb00020.x
528 Lazzerini, G., Lucchetti, S., Nicese, F.P., 2014. Analysis of greenhouse gas emissions from ornamental
529 plant production: A nursery level approach. Urban For. Urban Green. 13, 517–525.
530 doi:10.1016/j.ufug.2014.02.004
531 Liu, Q., Qin, Y., Zou, J., Guo, Y., Gao, Z., 2013. Annual nitrous oxide emissions from open-air and
532 greenhouse vegetable cropping systems in China. Plant Soil 370, 223–233. doi:10.1007/s11104-
533 013-1622-3
534 Maag, M., Vinther, F.., 1996. Nitrous oxide emission by nitrification and denitrification in different soil
535 types and at different soil moisture contents and temperatures. Appl. Soil Ecol. 4, 5–14.
536 doi:10.1016/0929-1393(96)00106-0
537 Maraseni, T.N., Qu, J., 2016. An international comparison of agricultural nitrous oxide emissions. J.
538 Clean. Prod. 135, 1256–1266. doi:10.1016/j.jclepro.2016.07.035
539 Marques, R., Oehmen, A., Pijuan, M., 2014. Novel microelectrode-based online system for monitoring
540 N2O gas emissions during wastewater treatment. Environ. Sci. Technol. 48, 12816–23.
541 doi:10.1021/es504061h
542 Mccall, D., Willumsen, J., 2015. Effects of nitrogen availability and supplementary light on the nitrate
543 content of soil-grown lettuce. http://dx.doi.org/10.1080/14620316.1999.11511137.
544 Merino, A., Pérez-Batallón, P., Macías, F., 2004. Responses of soil organic matter and greenhouse gas
545 fluxes to soil management and land use changes in a humid temperate region of southern Europe.
546 Soil Biol. Biochem. 36, 917–925. doi:10.1016/j.soilbio.2004.02.006
547 Mok, H.-F., Williamson, V.G., Grove, J.R., Burry, K., Barker, S.F., Hamilton, A.J., 2013. Strawberry
548 fields forever? Urban agriculture in developed countries: a review. Agron. Sustain. Dev. 34, 21–43.
549 doi:10.1007/s13593-013-0156-7
550 Montero, J.I., Antón, A., Torrellas, M., 2011. EUPHOROS deliverable 5. Report on environmental and
551 economic profile of present greenhouse production systems in Europe [WWW Document]. URL
552 http://www.euphoros.wur.nl/UK

553 Payen, S., Basset-Mens, C., Perret, S., 2015. LCA of local and imported tomato: an energy and water
554 trade-off. J. Clean. Prod. 87, 139–148. doi:10.1016/j.jclepro.2014.10.007
555 Pfab, H., Palmer, I., Buegger, F., Fiedler, S., Müller, T., Ruser, R., 2011. N2O fluxes from a Haplic
556 Luvisol under intensive production of lettuce and cauliflower as affected by different N-fertilization
557 strategies. J. Plant Nutr. Soil Sci. 174, 545–553. doi:10.1002/jpln.201000123
558 Pihlatie, M., Syväsalo, E., Simojoki, A., Esala, M., Regina, K., 2004. Contribution of nitrification and
559 denitrification to N2O production in peat, clay and loamy sand soils under different soil moisture
560 conditions. Nutr. Cycl. Agroecosystems 70, 135–141. doi:10.1023/B:FRES.0000048475.81211.3c
561 Rochette, P., Worth, D.E., Lemke, R.L., McConkey, B.G., Pennock, D.J., Wagner-Riddle, C., Desjardins,
562 R.J., 2008. Estimation of N 2 O emissions from agricultural soils in Canada. I. Development of a
563 country-specific methodology. Can. J. Soil Sci. 88, 641–654. doi:10.4141/CJSS07025
564 Ruser, R., Schulz, R., 2015. The effect of nitrification inhibitors on the nitrous oxide (N 2 O) release from
565 agricultural soils-a review. J. Plant Nutr. Soil Sci. 178, 171–188. doi:10.1002/jpln.201400251
566 Sanyé-Mengual, E., Oliver-Solà, J., Montero, J.I., Rieradevall, J., 2015. An environmental and economic
567 life cycle assessment of rooftop greenhouse (RTG) implementation in Barcelona, Spain. Assessing
568 new forms of urban agriculture from the greenhouse structure to the final product level. Int. J. Life
569 Cycle Assess. doi:10.1007/s11367-014-0836-9
570 Savvas, D., Gianquinto, G., Tuzel, Y., Gruda, N., 2013. Chapter 12. Soilless culture, in: Good
571 Agricultural Practices for Greenhouse Vegetable Crops: Principles for Mediterranean Climate
572 Areas. pp. 303–304.
573 Torrellas, M., Antón, A., López, J.C., Baeza, E.J., Parra, J.P., Muñoz, P., Montero, J.I., 2012. LCA of a
574 tomato crop in a multi-tunnel greenhouse in Almeria. Int. J. Life Cycle Assess. 17, 863–875.
575 doi:10.1007/s11367-012-0409-8
576 UN, 2012. World Population Prospects: The 2012 Revision. New York.
577 Weier, K.L., Doran, J.W., Power, J.F., Walters, D.T., 1993. Denitrification and the Dinitrogen/Nitrous
578 Oxide Ratio as Affected by Soil Water, Available Carbon, and Nitrate. Soil Sci. Soc. Am. J. 57, 66.
579 doi:10.2136/sssaj1993.03615995005700010013x
580 Xiong, Z., Xie, Y., Xing, G., Zhu, Z., Butenhoff, C., 2006. Measurements of nitrous oxide emissions from
581 vegetable production in China. Atmos. Environ. 40, 2225–2234.
582 doi:10.1016/j.atmosenv.2005.12.008
583 Yoshihara, T., Tokura, A., Hashida, S., Kitazaki, K., Asobe, M., Enbutus, K., Takenouchi, H., Goto, F.,
584 Shoji, K., 2014. A Precise/Short-interval Measurement of Nitrous Oxide Emission from a
585 Rockwool Tomato Culture. Environ. Control Biol. 52, 137–147. doi:10.2525/ecb.52.137
586