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DOI
10.1016/j.jclepro.2017.03.048

Publication date
2017

Document Version
Final published version

Published in
Journal of Cleaner Production

Journal of Cleaner Production 151 (2017) 10–20

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

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ARTICLE INFO

Article history:
Received 29 January 2016
Received in revised form
31 January 2017
Accepted 8 March 2017
Available online 8 March 2017

Keywords:
Land scarcity
Floating urbanization
Water-food-energy nexus
Coastal cities
Climate adaptation
Resilience

ABSTRACT

The disruption of nutrient cycles caused by human activities such as agriculture and burning fossil fuels is impacting ecosystem services on global and local scales. The increasing concentration of carbon dioxide in the atmosphere contributes to rising global temperatures and ocean acidification, whereas the accumulation of nutrients in water systems is leading to degradation of water quality and biodiversity. City populations play a major role in carbon dioxide and nutrient emissions as 'end consumers' of resources. The current challenge towards more resource-efficient cities is to transform urban metabolism from linear to cyclical. Discharged nutrients and carbon dioxide can be used as input for algae, which fixate carbon very efficiently into energetic storage compounds as starch or lipids. However, cities often lack the space to implement large-scale algae production. This article evaluates the potential of reusing nutrients and carbon dioxide to produce algae, food and biofuel on water nearby coastal and delta cities. First, nutrients and carbon dioxide discharge is estimated and two scenarios are developed. From the cities nutrient production, the potential algal yield is evaluated and translated into feed, food and oil yields. Two delta cities are chosen as case studies: Rotterdam and Metro Manila. The conclusion of this article is that Floating Production can help cities increasing their resilience in the field of food and energy. Floating Production can also contribute to a solution for global land shortage. The combination of food and energy production with floating urban development provides a climate-proof urban expansion in delta and coastal areas.

1. Introduction

As pointed out by the Millennium Ecosystem Assessment, human activities such as agriculture and burning fossil fuels have significantly altered nutrient cycles and increased the 'leakiness' of ecosystems (Millennium Ecosystem Assessment, 2005). The disruption of cycles as carbon and nitrogen is causing phenomena as ocean acidification and eutrophication, leading to environmental degradation of water quality. Increasing carbon dioxide (CO_2) and nutrient emissions are affecting ecosystem services both on global and local scales. City populations play a major role in carbon dioxide and nutrient emissions as 'end consumers' of resources such as fossil fuels and food. Currently, cities are almost entirely dependent on surrounding regions for providing food and energy to sustain urban population and activities (Pincetl et al., 2012). Urban areas import, consume and discharge large amount of nutrients. Studies on urban metabolism show that cities often have a linear usage of resources and waste production, with impacts on natural resources availability and environmental quality (Kennedy et al., 2011; Leduc and Van Kann, 2013). The current challenge towards more resource-efficient cities is to transform cities metabolism from linear to cyclical (Agudelo-Vera et al., 2012; Lowe and Evans, 1995; Patrício et al., 2015), in a way that discarded material becomes resource for another process. Nutrients imported by cities are rarely reused after consumption, even though they are critical for the global food production (Keyzer, 2010). Instead, nutrients are often removed or discharged into the environment. At the same time the reduction of greenhouse gas emissions is a global concern. The increasing concentration of greenhouse gases in the atmosphere contributes to rising global temperatures, causing sea level rise and increasing the amount of extreme weather events such as

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http://dx.doi.org/10.1016/j.jclepro.2017.03.048
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floods, storms and droughts (IPCC, 2012).

A possible way to recycle nutrients and carbon dioxide is to use them as input for algae cultivation. Algae are among the most optimum organisms for CO_2 sequestration because of their ability to fix carbon by photosynthesis, which is up to 50 times faster than terrestrial plants (Wang et al., 2008). As long as algae cultivation can be sufficiently contained in space, size or time, the negative impacts of large biomass production on water environments can be prevented. The large concentration of nutrients and carbon dioxide in urban areas make cities interesting locations for local recycling of 'waste'. However, dense urban environment often lack the space to implement large-scale algae production. A solution is to accommodate algae cultivation on the water, realizing floating systems for biofuel and food production.

This article evaluates the potential of reusing nutrients and CO_2 to grow algae on floating systems situated in the proximity of existing delta and coastal cities. Algae are used as the base for food and energy production. Oil and feed are extracted from algae. Feed is used as input for fish grown in aquaponic systems on water. Next to the floating production of food and energy, urban development could take place. Currently, floating development is gaining more and more attention and becoming part of cities programs for sustainable development and climate adaptation (Ernst et al., 2015). Combining production facilities with urban environment will increase economic feasibility and at the same time offer a climate-proof expansion for a growing urban population.

2. Methods

Several studies have been done on the use of algae for treatment of wastewater streams (Li et al., 2011; Manninen et al., 2015; Wang et al., 2010), on their potential for biofuel production and carbon dioxide sequestration (Borowitzka and Moheimani, 2013; Chisti, 2007; Cuellar-Bermudez et al., 2015; Sudhakar and Premalatha, 2012), and also on their use as a source of animal feed and other products (Becker, 2007; Belay et al., 1996). However, an integral study that investigates opportunities to recycle 'waste' from urban areas to provide valuable products for local use has never been conducted. This paper aims at opening the field for further research and projects on Floating Production. To estimate the potential of recycling nutrients and CO_2 from existing cities through Floating Production (FP), a calculation model was set up, consisting of the following parts:

1) *algae production input*: nutrients (nitrogen and phosphorous) excreted by a city's population and carbon dioxide emissions from industries;
2) *products yield*: calculation of algae biomass, oil, feed and food;
3) *food and energy resilience*: estimation of the contribution of Floating Production in providing local food and biofuel;
4) *influence on land use* of Floating Production, both on a local and global scale.

A scheme with these four steps and their relation is included in Fig. 1. Each part of the calculation model was based on methods, formulas and data that was collected from several literature sources. The amount of nutrients excreted by a city's population (part 1a), was derived from protein consumption data, which is more readily available (Jönsson et al. (2004)). The flows of nutrients after excretion were also investigated, based on available literature about treatment methods, extent and efficiency. Two scenarios were developed. The first scenario looked into the current treatment methods, including Floating Production as post-treatment. The second scenario considers the total potential that can be used for Floating Production. Research on algae was used to estimate algae yields in the two different scenarios (part 2a). Algae yields were estimated using a global composition formula of algae reported by Flesch et al. (2013) and taking into account different photosynthetic efficiencies, as calculated in the paper by Sudhakar and Premalatha (2012). Based on algae biomass, oil, feed and aquaponics yields were estimated (part 3b). The calculation for fish and vegetable yields from aquaponic systems used FAO (2014), Tartiel et al. (2008) and Rakocy (2012) as main sources.

The extent to which Floating Production can contribute to urban resilience (part 3) was evaluated comparing calculated yields with a city's consumption in terms of energy and food. The estimation of the agricultural land that could be 'saved' growing part of the food and energy consumed by city population (part 4) was performed using FAO data on global land use and domestic supply (FAOSTAT, 2014a, 2014b). The forest area that would be required to compensate for the carbon dioxide emissions of land agriculture was also taken into account. If part of the consumed food is grown on water, the sequestration space necessary to offset emissions from food production is reduced. The influence of Floating Production on land use and emissions was estimated using data by Gerber et al. (2013).

The calculation model was tested using two case studies: a rapidly urbanizing megacity in a developing country and a city in a developed nation. The case studies were selected among an inventory of coastal cities with pollution issues, high CO_2 emissions, high population density and growth rate. For this paper, Metro Manila and Rotterdam were chosen. Metro Manila was selected as an example of an urban area with environmental pollution, high population density and growth (Chang et al., 2009; Kelley and Williamson, 1984). Rotterdam was chosen for its high CO_2 emissions (Plomp et al., 2013). Both cities were defined using their administrative boundaries. Based on administrative boundaries, data on area and population were found. For Rotterdam and Metro Manila literature surveys was executed to gain insight in nutrient collection and treatment systems. The four parts of the calculation model are further explained and discussed in the following paragraphs, using Rotterdam and Metro Manila as case studies.

3. Calculation model

3.1. Nutrients from domestic wastewater and scenarios (part 1a)

In cities, large amount of nutrients are imported in the form of food which is consumed by people. After consumption, most of the nitrogen and phosphorus are excreted. In the past, human excreta were used as fertilizer. Currently, nutrients are usually collected by sewer systems and either treated in wastewater treatment systems or directly discharged to the river or sea. In both cases, most nutrients are no longer reused as resources for food production. The amount of nutrients excreted per capita is related to the diet and is estimated using data on food supply from FAOSTAT (2014b). To calculate the nutrients excreted, it was assumed that the food consumed per capita in a city is equal to the national average. The amount of nitrogen (N) and phosphorus (P) excreted per city inhabitant was computed based on protein consumption data provided by FAOSTAT (2014b) and on the equations proposed by Jönsson et al. (2004).

Additional source of phosphorus in domestic wastewater are detergents. Assuming a detergent load proportion of 1/5 compared to human P load (Kalmykova et al., 2012), the contribution of detergent used per person per year was estimated. The total nutrients produced per capita in the two cities is equal to 5.09 kg/cap/yr N and 0.68 kg/cap/yr P in Rotterdam and 2.89 kg/cap/yr N and 0.46 kg/cap/yr P in Metro Manila.

The values above refer to domestic wastewater nutrients potentially available for reuse in each city. However, nutrients that

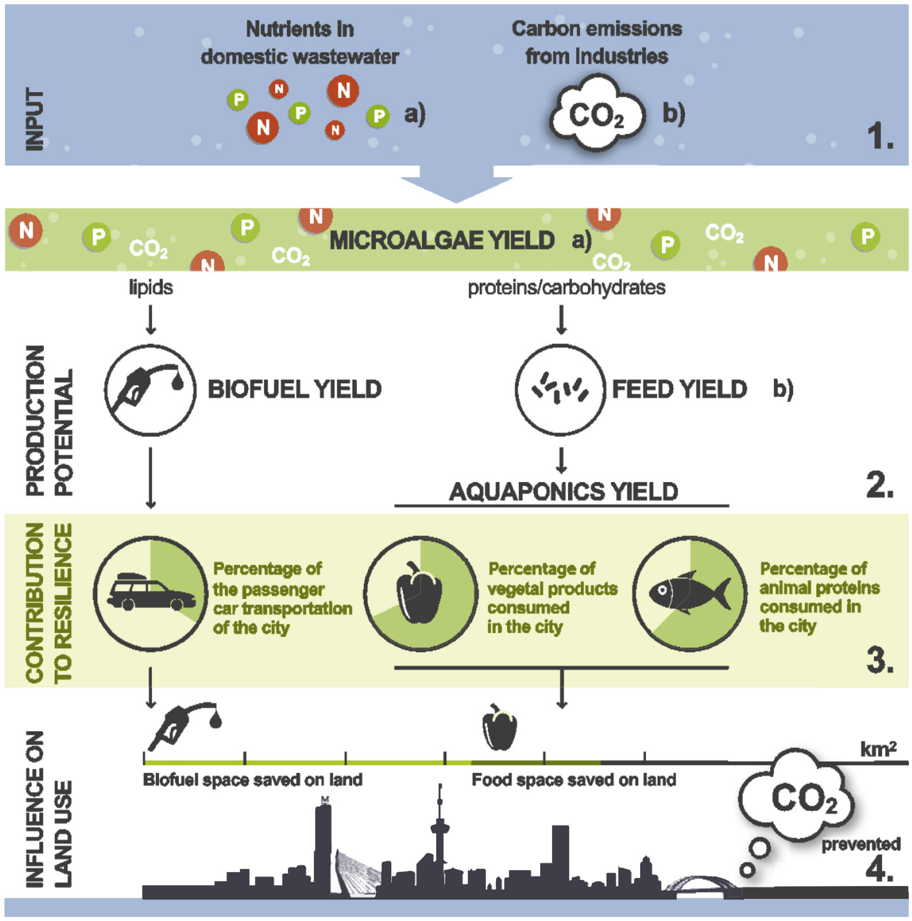

Fig. 1. Scheme of the calculation model.

can be recycled are much less due to type, characteristics, efficiency and losses of already adopted treatment systems. In cities where sewage collection and treatment are present, most nutrients are removed. In wastewater treatment plants (WWTPs), more than 50% of the nitrogen is transferred to the atmosphere, from where it can be fixed again through biological and industrial processes (Svirejeva-Hopkins and Reis, 2011). The remaining nitrogen is found in effluent water and sludge. Most of the phosphorus that is removed from wastewater accumulates in the sludge (Kalmykova et al., 2012). Cities that are not provided with sewage collection systems usually rely on local septic tanks to primarily treat black water. When septic tanks are poorly constructed and maintained, large amount of nutrients leak into the environment, polluting rivers and groundwater. In these contexts, nutrients from domestic wastewater are likely to be found mostly in water bodies and their sediments, in a diluted form. When septic tanks are regularly desludged and septage is collected and transported to treatment facilities, treated nutrients can be safely discharged in the environment or even reused as fertilizer for crops (Strande et al., 2014).

Rotterdam and Metro Manila manage their sewage very differently and therefore nutrient flows follow different paths. An overview of P and N flows in Rotterdam and Metro Manila is reported in Fig. 2. In Rotterdam, 100% of the wastewater is collected and treated in wastewater treatment plants (WWTPs), whereas in Metro Manila the majority of the city population uses septic tanks or leaching pits (Marcotullio, 2007). For Metro Manila, plans are being executed to improve sanitation and achieve 100% sewerage cover by 2037 (Maynilad, 2011).

Using the information and data collected, two scenarios were investigated. The objective of this study is to gain insight on the possible effects of implementing Floating Production in Rotterdam and Metro Manila. An overview of the outlined scenarios is presented in Table 1. The 'Post-Treatment' scenario investigates the opportunity of recycling nutrients after treatment by currently adopted systems. In this scenario, sludge from septic tanks and nutrients that are left after treatment in WWTPs (both in sludge and effluents) are post-treated on floating facilities. This strategy allows the recycling of nutrients that would otherwise end up in the environment. The second scenario, called 'Total Potential', expresses the potential available from domestic wastewater in each city, investigating the effects of recycling 100% of the nutrients via Floating Production. A comparison among N and P percentages used in both scenarios is reported in Table 1.

3.2. Emissions from industries and recovery technologies (part 1b)

Next to nitrogen and phosphorus, carbon dioxide requirement of algae is considered. Feeding algae with exhaust gases from industrial plants offers the opportunity to productively reuse CO_2, reducing environmental pollution. For this purpose, capturing technologies were investigated. There are promising CO_2-recovery technologies in development such as 'Oxy-fuel Combustion', in which fossil fuel is combusted with pure oxygen to create almost pure CO_2 emission. Capturing capacity of such plants is potentially 20–30% of the emissions of a typical refinery (Carbon Capture Journal, 2013). Another technology that is already regarded as a

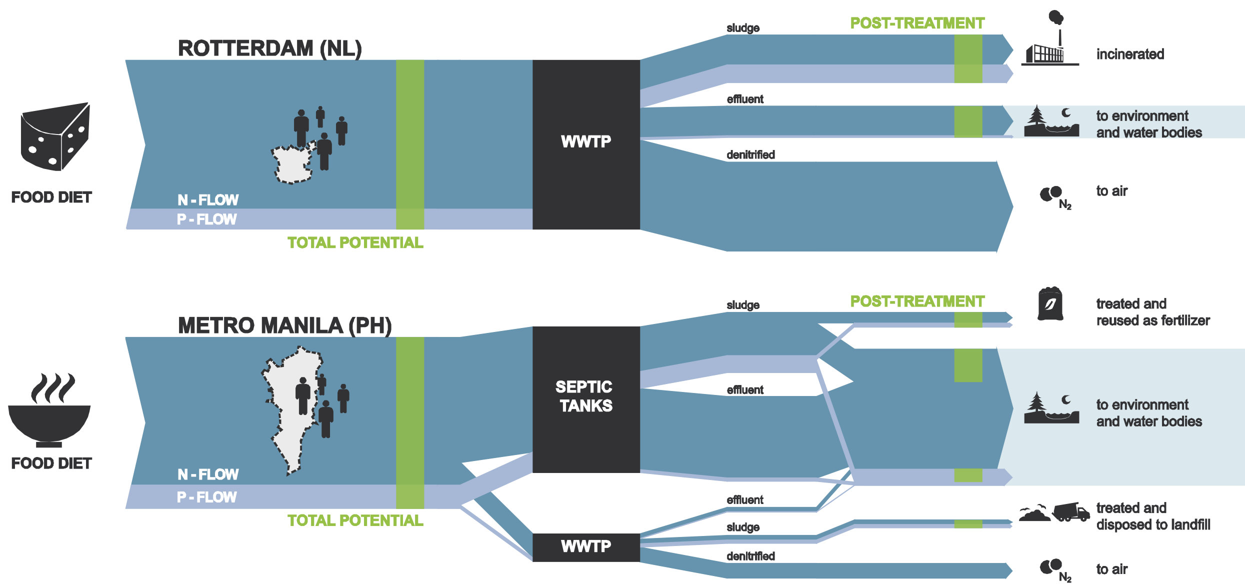

Fig. 2. Sewage management overview for Rotterdam and Metro Manila, values expressed in percentage.

Table 1
Post-Treatment and Total Potential scenarios for nutrient recycling through Floating Production (FP).

Scenarios	Description	Rotterdam		Metro Manila	
		recovered N	recovered P	recovered N	recovered P
Post-Treatment	Sludge from septic tanks and WWTPs is collected by trucks and treated by FP; effluents from WWTP are treated by FP.	Sludge, 20% Effluent, 20% Total, 40%	Sludge, 90% Effluent, 10% Total, 100%	Sludge, 33% Effluent, 3% Total, 36%	Sludge, 86% Effluent, 2% Total, 88%
Total Potential	All the wastewater is directly treated by FP.	Total, 100%	Total, 100%	Total, 100%	Total, 100%

"transformational" technology is 'Chemical Looping Combustion' (CLC). It uses metal oxides instead of pure oxygen and the separation of CO_2 is inherent to the process. Such technology could capture nearly all of the emissions without affecting the production efficiency of the plant (Global CCS Institute, 2012).

The amount of carbon dioxide that can be captured and used as input for algae production was estimated from International Energy Agency data on CO_2 emissions (IEA, 2014). For the calculation it was assumed that a city's emissions per capita are equal to the average emissions per person in the country. For Rotterdam, CO_2 emission from 'electricity and heat production' and 'other energy industry own use' is around 3874 kg/cap/yr, whereas in Metro Manila it is 394 kg/cap/yr. If technologies such as 'Oxy-fuel Combustion' and 'Chemical Looping Combustion' (CLC) are used, an average of 969 to 3680 kg CO_2/cap/yr in Rotterdam and 99–374 kg CO_2/cap/yr in Metro Manila could be available for algae production.

In the calculation model, carbon dioxide usage in algae cultivation was taken into account. Assuming a carbon content of 48% in algae, it follows that producing 1 kg dry algal biomass requires 1.8 kg CO_2 circa. However, carbon dioxide usage of the system is several times higher, because of poor absorption efficiency of CO_2 in water (Nayak, 2013). In the calculation, efficiency of CO_2 fixation was assumed to be equal to 30%.

3.3. *Algae biomass yield (part 2a)*

The term 'algae' has no taxonomic standing. In this article, it is defined as "photosynthetic protists and their multicellular allies" (Douglas et al., 2003). Using the energy from the sun, algae are able to fixate CO_2 into energetic storage compounds such starch or lipids (also commonly called 'oil'). Algal lipids can be used as building blocks in the production of biodiesel. While reproducing, algae consume inorganic nutrients from the water. A wide range of oil contents (15–85%) has been reported across diverse groups of species (Weyer et al., 2010). The high oil contents are usually achieved when the algae are exposed to 'stress' conditions, such as during nitrogen limitation and when they are no longer reproducing (Stephens et al., 2010). The protein content of algae biomass varies from 10% to 70%, with an average of 40%, comparable to meat and soy (Gouveia et al., 2008). Because of their well-balanced chemical composition, algae can be used as food for humans, but also as feed for fish and other animals. For the purpose of biofuel and food production microalgae are more preferable than macroalgae (seaweed). The preference to microalgae is due to its less complex structure, fast growth rate, high oil content (Sudhakar and Premalatha, 2012) and higher suitability for contained growth. In addition, microalgae take up nitrogen faster than macroalgae (Hossain et al., 2008), which makes microalgae an interesting option for nutrients removal from surface water and wastewater.

Algae productivity is related to the climate conditions and to the availability of sunlight throughout the year, and varies according to the photosynthetic efficiency. In the calculation model, algae yields were estimated using weather data and photosynthetic efficiency, as described by Sudhakar and Premalatha (2012). For each city, estimates of algae biomass production in ponds were performed, including 'optimistic', 'pessimistic' and 'most likely' scenarios, with photosynthetic efficiencies of 11.42% (theoretical maximum efficiency), 6% and 3% respectively. For the calculation, open ponds were used as cultivation systems. Open pond systems offer advantages compared to closed photobioreactor systems in terms of energy input and ease of operation. Recent work by Mooij et al. (2013) showed that one of the main disadvantages of open pond systems, contamination by less productive species, can be overcome by creating a selective environment. The temperature for the culture was assumed to be optimal and the energy-input of the microalgal cultivation was assumed to be covered by renewable resources, such as wind- or tidal power. Algae yield was estimated based on a global composition formula of algae, as described by Flesch et al. (2013): 48% carbon, 4.6% nitrogen and 0.99% phosphorus. A lipid content of 30% was chosen. Higher lipid content can be achieved, but with lower biomass yields. Since the estimation is not only focused on biofuel, but values feed production, it was decided to maximize algae productivity instead of lipid yield.

3.4. Feed, algae oil and aquaponics yields (part 2b)

From the algal biomass, feed and oil yields were estimated. In this research it was assumed that proteins and part of the lipids from algae are used as fish feed. Fish is farmed in combination with vegetable production in aquaponic systems. Aquaponics is a food production system based on a closed loop of nutrients: nutrients enter the system as fish feed, are consumed and excreted, processed by bacteria and finally supplied to vegetables as fertilizer. The calculation model estimates fish yields in aquaponics, based on the amount of available feed. The selected fish is tilapia, a common variety grown in aquaculture systems. Tilapia's diet generally consists over 90% of aquatic macrophytes, algae and diatoms, and includes a small percentage of aquatic insects, crustaceans and fish eggs (Khallaf and Alne-na-ei, 1987). In the calculation model it was assumed that most of the fish feed consists of algae. Next to algae, offal from processed fish grown within the system is used as feed. It was assumed that 25% of the fish weight is offal. Fish feed consists of 4% unprocessed algae, 81% algae cake after lipid extraction and 15% fish offal. The aquaponic system was dimensioned based on the feeding rate ratio of fish. This is equal to the amount of feed daily fed to fish, per square meter of plant area. According to a FAO technical paper on aquaponics, the optimum feeding rate ratio varies from 40 to 50 g/m^2/day for leafy vegetables and from 50 to 80 g/m^2/day for fruiting ones (FAO, 2014). Based on the area that is available for plants production, total vegetable yield were calculated for cucumber, tomato and basil.

Next to fish and vegetable yields, algae oil yields were estimated. It was assumed that lipid content in microalgae is equal to 30%. For the conversion from lipids to oil, the specific gravity of algae oil coefficient was applied, which is equal to 0.85 kg/l (Sudhakar and Premalatha, 2012).

3.5. Contribution to resilience (part 3)

The Rockefeller Foundation defines 'resilience' as *"the capacity (…) to survive, adapt, and grow in the face of stress and shocks [catastrophic events, either natural or manmade], and even transform when conditions require it"* (The Rockefeller Foundation, 2015). Resilient systems depend on the availability of supporting resources such as food and energy. In this research, the contribution of Floating Production to the cities resilience was estimated, specifically from the perspective of local food and energy production. Vegetable and fish yields were compared to vegetal products and animal protein consumption in Rotterdam and Metro Manila, using FAOSTAT data (FAOSTAT, 2014b). The contribution to passenger vehicle fuel supply was estimated comparing biofuel yields with country statistics on passenger cars, using World Development Indicators (The World Bank, 2012) and data from the United States Environmental Protection Agency (EPA, 2014).

3.6. Influence on land use (part 4)

The effects of producing food and biofuel through Floating Production were estimated, comparing the area requirements for production on land with the ones on water. Most of the space that cities require for food and energy production is located outside of the city borders but cannot simply be deemed deficient. The land use estimation compares the amount of area that a given population requires to sustain their current lifestyle with the globally available land area. The amount of food production area that is required by Rotterdam and Metro Manila was estimated based on FAOSTAT data on average food supply per country and global agricultural land (FAOSTAT, 2014a, 2014b). The area for vegetal products for human consumption was calculated from the total agricultural area, excluding 'permanent meadows and pastures', which are used to grow herbaceous forage crops. Since 1/3 of the total crops are used as animal feed (FAO, 2013), the area for vegetal products for human consumption is $15.5 \times 2/3 = 10.3$ million km^2. The agricultural area required for animals is therefore $33.6 + 15.5 \times 1/3 = 38.8$ million km^2 ('permanent meadows and pastures' and area for feed production). Efficiency of meat and vegetal products was estimated on a global scale and, according to food supply data and urban population, the area required for food was calculated both for Rotterdam and Metro Manila. The calculation is reported in Table 2. The global land area required to grow meat and vegetal products consumed within the two cities is 11,994 m^2/cap/yr for Rotterdam and 6564 m^2/cap/yr for Metro Manila.

Next to the food production area, agricultural emissions due to meat and vegetal production on land were estimated using data by Gerber et al. (2013). According to the calculation, the emissions from food production are 2.5 tCO_{2eq}/cap/yr for Rotterdam and 1.1 tCO_{2eq}/cap/yr for Metro Manila. The area required to sequester emissions from agriculture was then added to the land use estimation. The total contribution of Floating Production in reducing land shortage was calculated, taking into account the amount of area that could be saved on land by producing part of cities food consumption on water.

4. Results

Results from each part of the calculation model are reported below for the two cities. Estimations of nutrients and CO_2 were used as input for calculating the algae biomass productivity in the two cities. A comparison between Floating Production in Rotterdam and Metro Manila shows that Metro Manila offers more optimal conditions for algae growth. Higher productivity can be obtained with the same amount of area. With a photosynthetic efficiency of 3%, 6 kt of algae biomass/km^2/yr are produced in Rotterdam and over 10 kt/km^2/yr in Metro Manila. Algae biomass productivity influences the amount of feed and lipids that can be extracted from algae. Assuming that algae cake is used as major feed supplement for fish and a constant aquaponics production, a larger algae production area is required in Rotterdam to grow the same amount of fish feed than in Metro Manila. Compared to Metro Manila, which has a feed productivity of 7.44 kt/km^2/yr at 3% photosynthetic efficiency, Rotterdam's feed production is equal to 4.58 kt/km^2/yr. The same consideration is valid for lipids: lipid productivity in Rotterdam is around 1.8 kt/km^2/yr, whereas in Metro Manila productivity reaches almost 3 kt/km^2/yr (considering a photosynthetic efficiency of 3%). Fig. 3 includes an overview of algae productivities at different photosynthetic efficiencies. In the graphs below, aquaponics is included.

Using estimated productivity values of algae and aquaponics, yields from Floating Production were calculated for the cities of

Table 2
Average global land area and carbon dioxide emissions from food production for the cities of Rotterdam and Metro Manila.

	Global					Rotterdam			Metro Manila		
	Prod. (Mt)[a]	Emiss. ($MtCO_{2eq}$)[b]	Emiss. intensity (gCO_{2eq}/g prod)	Area (mln km^2)[a]	Yields (t/km^2)	Dom. supply/ cap (kg)[a]	Food area (m^2/cap)	Emiss. (tCO_{2eq}/cap)	Dom. supply/ cap (kg)[a]	Food area (m^2/cap)	Emiss. (tCO_{2eq}/cap)
Meat[c]	259.2	4373	16.9	38.8	6.7	79	11,809	1.3	34	5150	0.4
Vegetal	6900	5300	0.8	10.3	669.9	1456	186	1.1	947	1414	0.7
Total[d]	7861	12,367	1.6	49.1	676.6	1535	11,994	2.5	981	6564	1.1

[a] Values calculated using data from FAOSTAT (2014a,b).
[b] Emission data from Gerber et al. (2013).
[c] Includes bovine, small ruminant/other, pig, chicken.
[d] The total can differ from the sum of the rounded values.

Rotterdam and Metro Manila. Two scenarios, 'Post-Treatment' and 'Total Potential', are used to estimate the contribution of Floating Production in recycling nutrients from wastewater. Fig. 4 includes the comparison between Rotterdam and Metro Manila, for both scenarios. Although consumption patterns of Rotterdam's population lead to higher nutrient emissions per capita compared to Metro Manila, the average population density in Rotterdam is six times smaller than the one of Metro Manila. This results in a lower nutrient density for Rotterdam compared to Metro Manila. For the comparison between the two cities, values per km^2 provide better insight on the potential for Floating Production for a city. Next to values per km^2 of city, per capita values are also reported in Fig. 4.

The estimation shows that algae biomass yields in the two scenarios range from 0.13 to 0.20 kt/km^2/yr for Rotterdam and from 0.42 to 0.87 kt/km^2/yr for Metro Manila. In Rotterdam, oil yields are equal to 39.74 m^3/km^2/yr for the Post-Treatment scenario and 61.79 m^3/km^2/yr for the Total Potential scenario. For Manila, yields were estimated around 126.50 m^3/km^2/yr and 262.08 m^3/km^2/yr

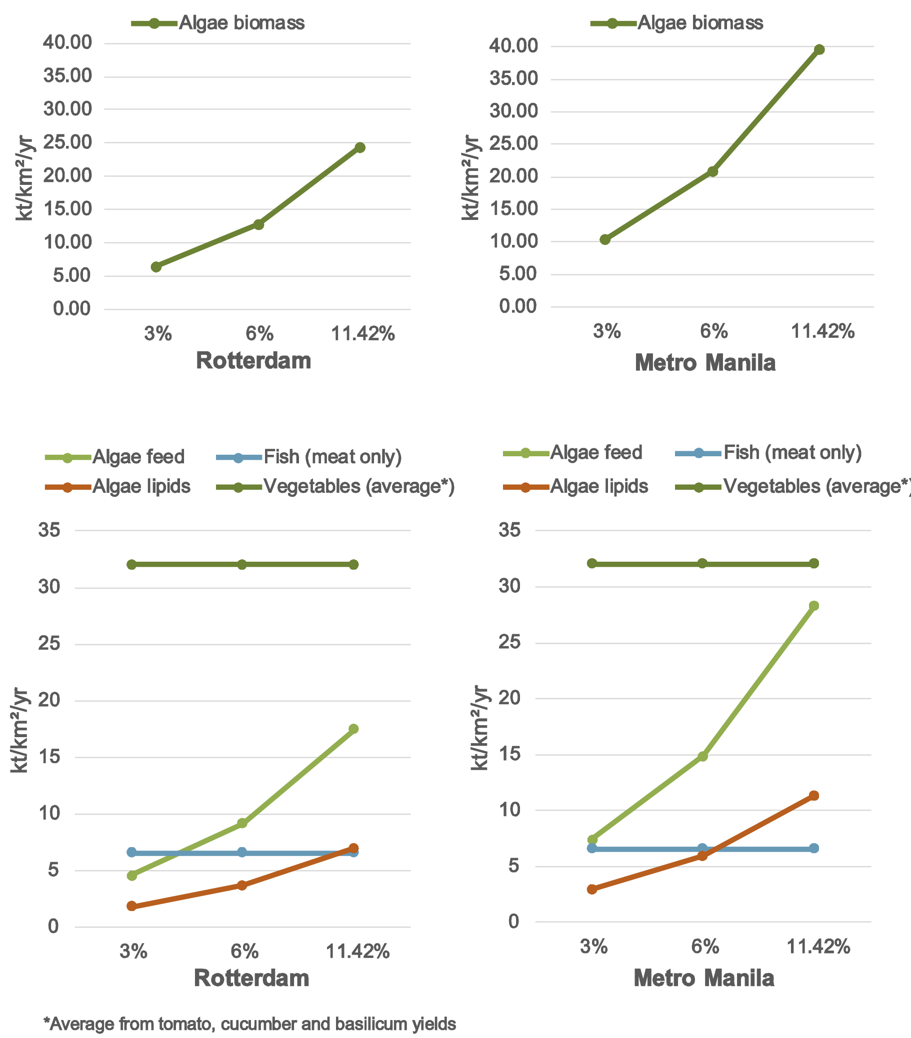

Fig. 3. Average algae biomass productivity at different photosynthetic efficiencies, values for Rotterdam and Metro Manila; (below) average feed, lipid, fish and vegetable productivity of Floating Production in Rotterdam and Metro Manila.

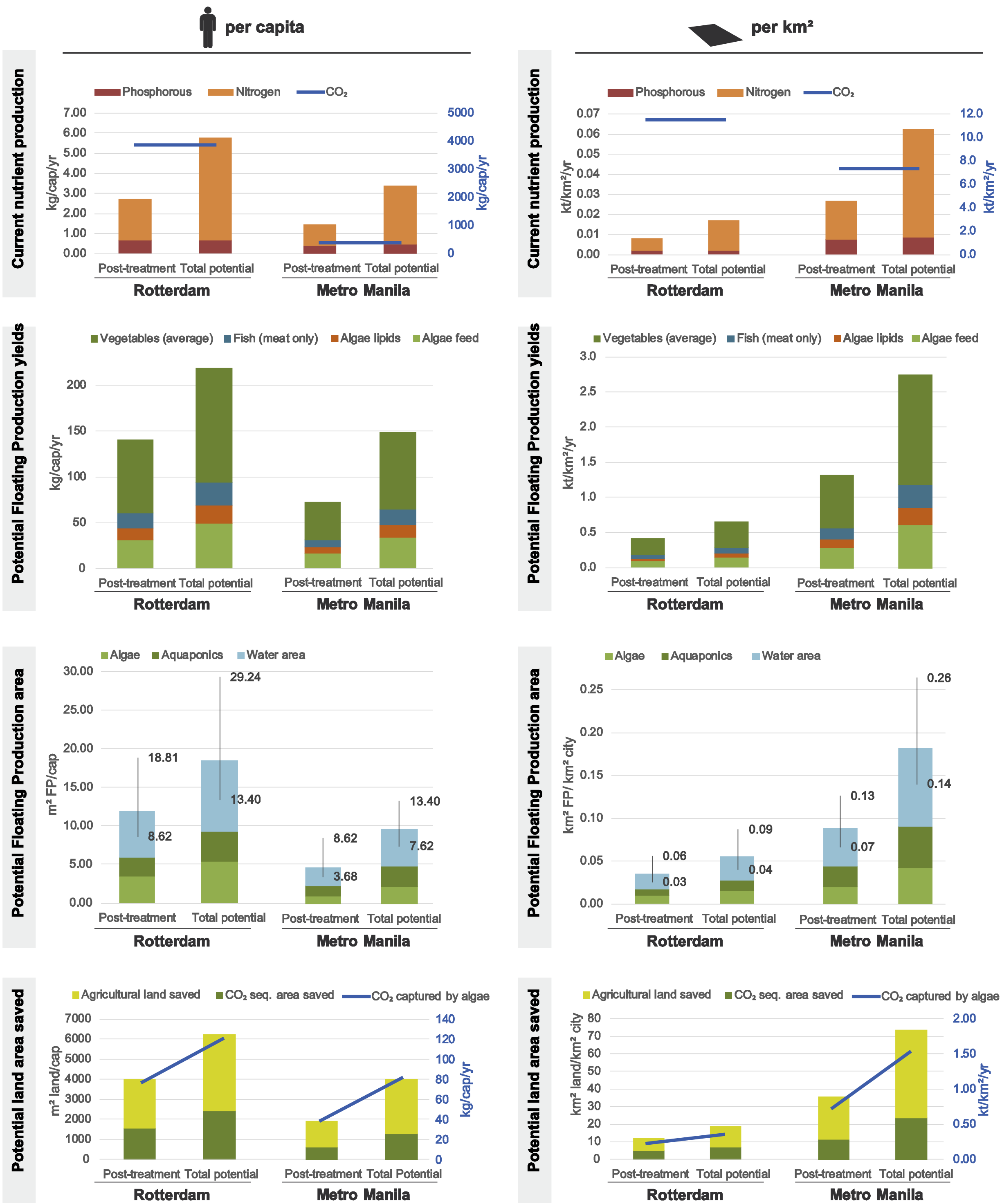

Fig. 4. Potential of Floating Production for Rotterdam and Metro Manila, values per capita and per km^2.

respectively. Aquaponics could produce up to 0.08 kt/km^2/yr of fish and 0.37 kt/km^2/yr of vegetal products in Rotterdam. In Manila, up to 0.32 kt/km^2/yr of fish and 1.57 kt/km^2/yr of vegetal products could be grown with the same system.

As shown by Fig. 3, algae biomass productivity is related to algae photosynthetic efficiency and to the solar radiation in the location. In the Total Potential scenario, the water surface required for algae and food production varies from 0.04 to 0.09 km$^2_{FP}$/km$^2_{city}$ for Rotterdam, and from 0.14 to 0.26 km$^2_{FP}$/km$^2_{city}$ for Metro Manila, considering a photosynthetic efficiency range between 11.42% and 3% respectively. The estimation of water surface requirements for Floating Production includes the water area between floating platforms. Results showed that growing fish and vegetables on floating systems can help reducing cities land requirement by choosing more efficient food production methods and producing local food. Up to 18.50 km$^2_{land}$/km$^2_{city}$ and 73.81 km$^2_{land}$/km$^2_{city}$ are saved globally through Floating Production in Rotterdam and Manila. To put those numbers in perspective, the land saved for the two cities is equal to 12 and 74 times the administrative area of Rotterdam and Metro Manila respectively. This estimation also takes into account the CO_2 sequestration area which is required to compensate for the carbon dioxide emissions caused by food production on land. In the Total Potential scenario, the CO_2 sequestration area that can be saved producing food and algae oil via Floating Production in Rotterdam and Manila is circa 7.20 $km^2_{seq.\ area}/km^2_{city}$ and 23.70 $km^2_{seq.\ area}/km^2_{city}$ respectively. For the Total Potential scenario, the average CO_2 captured by algae to grow their biomass is equal to 0.36 kt/km^2/yr for Rotterdam and 1.53 kt/km^2/yr for Metro Manila.

This research shows direct influence of Floating Production on the resilience of Rotterdam and Metro Manila. If 100% of domestic wastewater nutrients are recycled by Floating Production, aquaponics could provide 29% and 22% of the vegetal products consumed in the two cities respectively. At the same time, 20% and 37% of the average protein consumption is supplied by local fish production in the cities. As shown in the overview presented in Table 3, the estimated efficiency of Floating Production compared to average land agriculture is more than hundred times higher and ranges from 130 to 284 times for Rotterdam and from 189 to 355 times for Metro Manila. In addition to vegetables and fish, algae fuel is produced. The estimated amount of biofuel is enough to cover 2% and 93% of the passenger vehicles for Rotterdam and Metro Manila respectively. Those estimates consider an average fuel consumption of 534 gallons/yr/vehicle.

5. Discussion

5.1. Assumptions and limitations

This paper presents an estimation of the potential influence of Floating Production on the urban metabolism of delta and coastal cities. In the estimation, several assumptions were made. Losses from algae treatment were not considered, as well as energy requirements of systems. Optimal growing conditions were assumed. All the nutrients were considered to be directly available for algae growth. However, only dissolved nutrients in the form of ammonia, nitrate, nitrite and orthophosphate as well as dissolved CO_2 can be directly used by algae. The rest of the nutrients are found in the form of particles or gas and can be released into the water through chemical and biological processes. The amount of nutrients removed by algae depends on many factors such as algae and bacteria metabolism, wastewater composition, characteristics of the treatment system and pH, and should be evaluated for the specific cultivation system.

It is important to notice that the current estimation considers only nutrients from domestic wastewater. Next to wastewater, other sources of nutrients are present within cities, for example in surface water. Taking into account other nutrient sources would increase Floating Production. For a more complete estimation, data on water quality needs to be collected for each urban area. Analyzing all the nutrient flows within the city can ultimately help finding further connections and better strategies for nutrient recycling.

The model uses average country values to estimate nutrients and carbon dioxide produced by cities. Average country values are easily accessible and useful for a first estimation, but might substantially differ from emissions measured within a city. Therefore, for a more accurate calculation, data on nutrients and CO_2 flows in Rotterdam and Metro Manila should be used as input in the calculation model.

The estimation of the contribution to resilience from Floating Production reports the share of food and biofuel provided to city populations by floating systems. Resilience is related to the amount of nutrients that can be recycled. A 100% resilience could be theoretically achieved if all the nutrients are reused. In this paper, a conservative approach towards efficiency of food production systems was taken. The production system was based on rules that define the ratio between fish feed and plant growing area in raft aquaponics. According to Rakocy (2012), three to four times lower feed ratios could be used when other types of systems are chosen. Using those values as input would lead to more efficient nutrient recycling and to higher food yields.

5.2. Environmental impacts

Recent literature shows that the positive or negative balance of environmental impacts caused by algae production is related to the location and to how the system is configured (Flesch et al., 2013; Slade and Bauen, 2013; Usher et al., 2014). Environmental impacts of microalgae production on land may be related to fresh water consumption, (fossil fuel) energy input, GHG emissions, land use, nutrient pollution into aquatic systems, leakage of non-native or genetically modified strains in the environment (Slade and Bauen, 2013).

Various environmental impacts of floating microalgae cultivation might be comparable to land-based production, such as energy consumption and GHG emissions. To reduce energy consumption of algae systems it is fundamental to make clever use of environmental conditions such as energy flows, proximity to nutrients, CO_2 and water (Jacobi and Posten, 2013; Usher et al., 2014). A study by Flesch et al. (2013) showed that almost two-thirds of GHG emissions in ponds are due to the energy that is required to pump/mix pond water and to fertilizer input (which should balance the volatilization). Oil extraction and conversion into biodiesel account for almost 1/3 of the total GHG emissions. Since the largest part of GHG emissions in ponds come from algae growth, it is fundamental to maximize algal growth rate.

Looking at the life cycle assessment of algae biodiesel production, Flesch et al. (2013) concluded that reusing algae cake after lipid extraction can contribute reducing GHG emissions from the overall process. According to Flesch et al. (2013), when using the algae cake for anaerobic digestion, the GHG emission balance

Table 3
Contribution to resilience and efficiency of Floating Production in Rotterdam and Metro Manila for different scenarios.

Photosynthetic efficiency		Rotterdam				Metro Manila			
		Post-treatment		Total potential		Post-treatment		Total potential	
		3%	11.4%	3%	11.4%	3%	11.4%	3%	11.4%
Contribution to resilience	Share of vegetal consumption	19%	19%	29%	29%	11%	11%	22%	22%
	Share of protein consumption	13%	13%	20%	20%	18%	18%	37%	37%
	Share of passenger vehicles	1.5%	1.5%	2.4%	2.4%	45%	45%	93%	93%
Efficiency	Compared to land agriculture	130×	284×	130×	284×	189×	355×	189×	355×

becomes negative. Compared to anaerobic digestion, the use of algae cake as feed was found to be less effective in reducing the emissions (26% decrease compared to 232% of anaerobic digestion). However, considerable benefits of using algae feed arise from the possibility of offsetting part of the feed production on land. A recent study showed that replacing agricultural feed with algae feed could be one of the key strategies to achieve a significant reduction in atmospheric carbon dioxide concentration (Walsh et al., 2015).

Other impacts of floating algae production include the chance of nutrient leakage from floating ponds into aquatic ecosystems, which may lead to pollution and eutrophication of water bodies. Nutrient pollution already occurs in many cities where sewage collection and treatment are limited. In this respect, using nutrients to grow algae in contained environments could help reducing aquatic pollution. If algae are used to treat effluent water discharged from WWTPs after treatment process, no additional pollution is created compared to the current discharge. Moreover, since algae that are present in wastewater are fresh water algae, in case of system leakage they won't be able to survive in salt water (Harris et al., 2013).

Policy in European countries, including the city of Rotterdam, has aimed at reducing phosphorus over the past decades. Recent research shows that phosphorous reduction measures can lead to an imbalance of nutrients (Burson et al., 2016). This imbalance causes harmful species to proliferate and disturbs the lower trophic levels (which form the base of the aquatic food chain). The researchers suggest putting a halt to drastic removal of phosphorus and finding better ways of removing nitrogen. In this perspective, reusing waste nutrients (especially nitrogen) through Floating Production could help restoring the balance between nitrogen and phosphorus loads in aquatic ecosystems.

For algae production, ecology-based selective environments offer an alternative to choosing specific algae strains and creating environments ad-hoc where specific strains can thrive (Mooij et al., 2015). Focusing on the environment that gives a competitive advantage to algae with desired characteristics (e.g. high lipid content) could help reducing the inputs (herbicides, energy, etc.) that are necessary to maintain optimal system conditions. By creating ecology-based selective environments, native species are most likely to have a competitive advantage. In case of large floating open ponds, the risk of biological invasion in aquatic ecosystems caused by escape of non-native algae species (through leakages, aerosolization, wildlife vectors or turbulent water) are prevented when local strains are favoured.

Food production practices often severely affect the environment by polluting soil and water with fertilizers, animal waste and pesticides, inducing soil erosion and producing GHG. In comparison to such practices, aquaponics is often regarded as an ecologically-friendly food production system, which can be operated almost waste-free (König et al., 2016). As for microalgae ponds, possible negative impact might be caused by the leakage of ammonia from fish tanks. This can occur due to poor maintenance or events that damage or break floating ponds. If farmed fish species are different from wild ones, or are not native to the area, the escape of fish and disruption of aquatic ecosystem might also be a concern (Naylor et al., 2000).

During operation of floating algae and aquaponics systems, environmental monitoring is fundamental to be able to evaluate the impacts of production systems on water quality and ecology, but also to ensure that the structural integrity of platforms is not affected. Using underwater drones has been demonstrated to provide an easy, cost-effective and safer way to collect data and footages in zones near and under floating structures (de Lima et al., 2015).

5.3. Benefits of floating production

As demonstrated in the paper, benefits estimated for Rotterdam and Metro Manila include the contribution to resilience in the two cities and to reducing global land shortage. While recycling emissions from cities, Floating Production can help reducing the pressure on current resources, both on a local and global scale. Such benefits are often hard to quantify in economic terms. Many analyses that evaluate the economic feasibility of algae for biofuel (and for other products) are found in recent literature (Darzins et al., 2010; Norsker et al., 2011; Richardson et al., 2010; Slade and Bauen, 2013; to mention some of them). Such analyses aim at evaluating the economics of scaling up microalgae production to commercial-scale, estimating the costs of microalgae fuel in comparison with fossil fuel. Results show that costs of algae biofuel are often not yet competitive with petroleum diesel. However, in these analyses, environmental benefits that arise from much lower life-cycle CO_2 emissions compared to fossil fuels, from waste streams remediation, and from higher efficiency than land-based fuel crops (Dismukes et al., 2008) are often left out. The reason is that benefits towards ecosystems are hard to quantify, if not impossible. As explained in the paper by Spangenberg and Settele (2010, p. 335), "*there is no sound way to value ecosystem services beyond the immediate expenditures needed*". Although an 'objective' quantification of ecological services is impossible and therefore not helpful for defining political priorities, safeguarding and supporting ecosystem services can still be a political decision that does not require economic justification.

6. Conclusions

The objective of this study is to gain insight on the potential of Floating Production to help improving cities metabolism through reusing waste nutrients and carbon dioxide. In this paper, two cities with different climate, population density and waste emissions are compared and evaluated. From the comparison, it was concluded that climate is an important factor that affects the feasibility and efficiency of Floating Production. Environmental parameters such as temperature and solar radiation highly influence algae growth. Biomass growth rate, in turn, affects the energy requirements of the systems and the feasibility of Floating Production. For reducing the energy demand of the systems, it is fundamental to make the best use of energy and resource flows available. The proximity to sources of nutrients and carbon dioxide is also an important aspect to take into account while selecting locations for Floating Production.

This research demonstrated how Floating Production has the potential to provide a wide range of benefits to delta and coastal cities. Some benefits are local and directly experienced by cities, such as local food and oil production. Other benefits have global implication, as for example recycling waste and CO_2 emissions, preventing nutrients pollution and reducing pressure on current fish stock. The potential of Floating Production to reduce land scarcity and use CO_2 and waste nutrients in a productive way was investigated for two delta cities, Rotterdam and Metro Manila. The results showed that Floating Production can significantly reduce the global land area required for cities to sustain their current food and fuel consumption. However, to utilize the potential of Floating Production, implementation in practice as well as further research is needed. The relevance and importance will increase, as growing population and food consumption are putting more and more pressure on scarce land and available resources, requiring urgent actions and innovative solutions. Pilot projects are key in order to integrate building, food and energy production on water, demonstrating concepts which have not been applied in practice yet.

Acknowledgments

We thank the Centre of Expertise Delta Technology and the Topsector Water for providing funds for the research. The authors are also grateful to the comments from two anonymous reviewers who took time to read and give their feedback on the paper.

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