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Potential of floating productive developments for delta cities

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Abstract: Nutrients and CO_2 produced in densely populated areas ultimately accumulate in water systems, threatening the biodiversity of estuaries and coral reefs. At the same time nutrients essential for food security as phosphorous and nitrogen in forms that plants can absorb are becoming scarce. This article evaluates the potential of reusing nutrients and CO_2 to produce algae, food and biofuel in three delta cities: Rotterdam, Manila and Jakarta. First, nutrients and CO_2 produced by cities are estimated and several scenarios are developed. From the cities nutrient production, the potential algal yield is evaluated and translated into feed, food and biofuel yields. The conclusion of this article is that productive floating developments can help cities increasing their resilience in the field of food and energy. Floating developments 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.

Keywords: Land scarcity; floating urbanization; water-food-energy nexus; coastal cities; climate adaptation

Introduction

More than 150,000 people move from the countryside to the city every day, which means that in 2050 approximately 2 billion additional people will have been added to the urban population (UN, 2012). Urbanization is taking place mainly in coastal and riverine areas, because of the resources and services those areas provide. Currently, cities are almost entirely dependent on surrounding regions. Cities use resources as input and produce waste and emissions. To be more resource-efficient, cities have to close their cycles, in a way that waste of one component of the system becomes a resource for another. Urban population consumes and excretes large amounts of nutrients. However, nutrients are rarely reused, even though they are critical for the global food production. Instead, nutrients are discharged into the environment, removed or incinerated (in waste and sludge treatment plants). Cities are also important contributors to global greenhouse gas emissions, which are causing changes in air and ocean temperatures, ecosystems and biodiversity. Rising global temperatures cause sea level rise and increase the amount of extreme weather events such as floods, storms and droughts (IPCC, 2012). Delta and coastal cities are particularly vulnerable to these threats. This article evaluates the potential of reusing nutrients and CO_2 from delta cities to grow algae[1] in floating developments. Algae are one of the most optimum organisms for sequestration of CO_2 because of their ability to fix carbon by photosynthesis. In the

[1] The term algae has no taxonomic standing. In this article, it is defined as “photosynthetic protists and their multicellular allies” (Douglas, 2003).

paper, algae are used as the base for food and energy production, providing biofuel and feed for fish grown in aquaponic systems. In such developments, floating built environment is combined to production facilities, offering a climate-proof expansion for the growing urban population.

Material and Methods

First, three case studies were selected among an inventory of global cities with pollution issues, high CO_2 emissions, high population density and growth rate. From a list of potential candidates, Rotterdam, Manila and Jakarta were chosen for their high score in CO_2 emissions, pollution and population density and growth. Cities were defined using their administrative boundaries. Within administrative boundaries, area and population were estimated using available data. For Rotterdam, Manila and Jakarta a literature survey was executed to gain insight on collection and treatment of nutrients and on CO_2 emissions. A method described by Jönsson et al. (2004) was used to estimate nutrients excreted by the city population, based on average food consumption in each country. Scenarios were developed to investigate nutrient sources in each city. Scientific literature on algae was used to build a calculation model where algae yields are estimated, assuming optimal growing conditions. Fish and vegetables yields in aquaponic systems are calculated, using algae feed as main input. Biofuel yield was estimated. The extent to which floating developments can contribute to resilience, decreasing external dependence in the field of food and energy, was then evaluated.

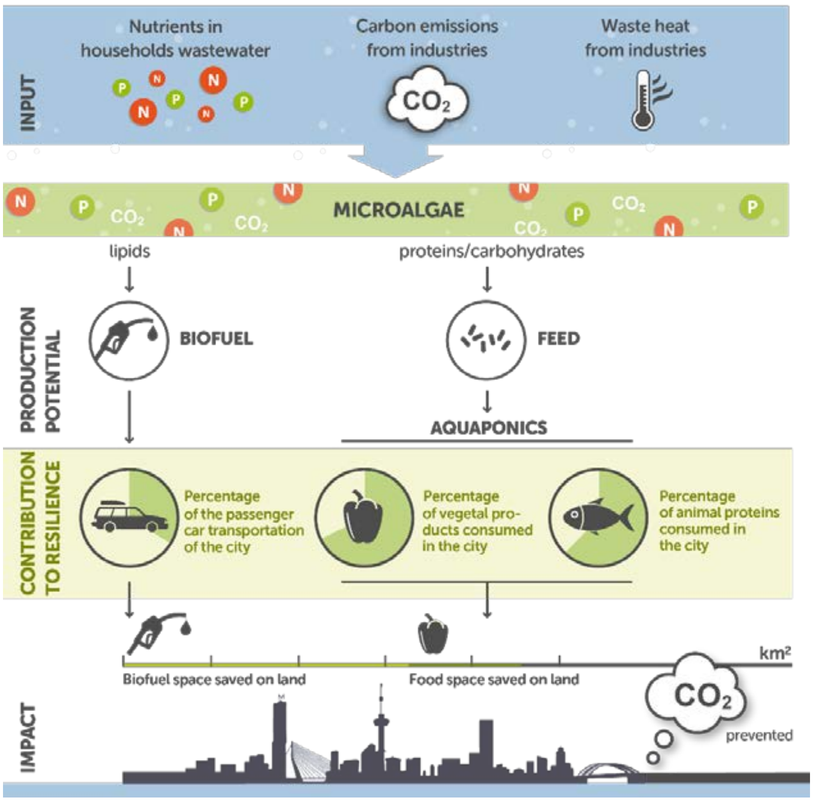

Figure 1 Scheme of the calculation model

Household wastewater nutrients availability: scenarios

In cities, nutrients are imported in the form of food 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 systems or directly discharged to the river or sea. In both cases, most nutrients are no longer reused as resources for food production. An estimation of the total amount of nutrients that is available in household wastewater can be performed multiplying the nutrients excreted per capita by the total population of a city. The amount of nutrients excreted per capita is related to the diet and is estimated using data on food supply from FAOSTAT (FAO, 2014). To calculate the nutrients excreted per capita it was assumed that the food consumed per capita in the three case studies is equal to the national average. The amount of nitrogen (N) and phosphorus (P) excreted per capita was computed based on protein values provided by FAOSTAT data and on the equations proposed by Jönsson et al. (2004). P and N coefficients were then multiplied by the city population.

Additional source of phosphorus in households wastewater are detergents. Research on phosphorus input for the wastewater treatment plant in Gothenburg (Sweden) shows that detergents P load is equal to approximately 1/5 compared to the human P load (Kalmykova, 2012). Assuming this proportion, the contribution of detergent used per person per year is estimated. The total amount of household wastewater nutrients estimated is 3.16 kt/yr N and 0.42 kt/yr P for Rotterdam; 34.33 kt/yr N and 5.48 kt/yr P for Manila; 26.78 kt/yr N and 4.71 kt/yr P for Jakarta.

The values above report the total nutrients potentially available for reuse in each city. However, nutrients that can be recycled are much less due to type, characteristics, efficiency and losses of adopted treatment systems. In cities where sewage collection and treatment are present, most nutrients are removed. In wastewater treatment plants, 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, 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, 2012). Currently this nutrient source is not used, but discharged in the environment or incinerated. Cities that are not provided with sewage collection systems usually rely on local septic tanks to primary treat black water. Since septic tanks are often poorly constructed and maintained, large amount of nutrients leak into the environment, polluting rivers and groundwater. In these contexts, nutrients from human 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, 2014).

Scenarios and strategies to recover nutrients in each of the three cities are developed taking into account wastewater collection extent and wastewater treatment systems and characteristics. Rotterdam, Jakarta and Manila manage their sewage very differently and therefore nutrient flows follow different paths. An overview of the sewage management of Rotterdam, Manila and Jakarta is reported in Figure 2. In Rotterdam, 100% of the wastewater is collected and treated in wastewater treatment plants (WWTPs), whereas in Manila and Jakarta the majority of the city population uses septic tanks or leaching pits. In Jakarta, about 1/5 of population relies on pit latrines and toilets that discharge directly into nearby drains and ditches. In some cases there are no facilities at all (Marcotullio, 2007).

Using the information and data collected, scenarios were developed to illustrate the possible effects of implementing floating productive developments (FPDs) in Rotterdam, Manila and Jakarta. Four scenarios are investigated adding FPDs as post-treatment or proposing them as an alternative treatment. Table 1 reports an overview of the outlined scenarios. Scenario 1 investigates the opportunity to recycle nutrients from the current adopted treatment system. Here, sludge from septic tanks and nutrients that are left after treatment in WWTPs (both in sludge and effluents) are post-treated in facilities on floating productive developments. This strategy allows recycling part of the nutrients that otherwise end up into the environment, polluting it. Scenario 2 assumes that Manila and Jakarta reach 100% cover of the sewage network and all the wastewater is treated in wastewater treatment plants, and post-treated by floating facilities. This scenarios considers plans that both cities are executing to improve sanitation. Manila in particular is planning to achieve 100% sewerage cover by 2018 (Cleofas, 2011). The connection of households with the wastewater collection network could strongly reduce pollution and decrease the occurrence of diseases. Alternatively, floating productive developments could be used as full treatment methods. Scenario 3 considers 50% of the nutrients treated by FPDs and 50% by traditional WWTPs, whereas scenario 4 investigates the impact of recycling 100% of the nutrients by FPDs, expressing the total potential available from household wastewater in each city. A comparison among the nutrients available in each scenario is reported in Figure 3.

CO_2 recovery estimation

Data on carbon dioxide emissions from energy production, industries and other productive sectors was collected and the opportunity to reuse CO_2 produced by the three cities was investigated. To be able to reuse the CO_2 produced the CO_2 produced must first be recovered. 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 to 30% of the emissions of a typical refinery (Carbon Capture Journal, 2013). Another technology that is already regarded as a “transformational” technology is Chemical Looping Combustion. 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). In the estimation it is assumed that CO_2 from power plants and industries is captured using the described technologies and used for algal growth. The calculation is performed using data from reports on CO_2 emissions by each city and takes into account the carbon dioxide requirements to grow algae.

Table 1 FPDs as wastewater treatment, implementation scenarios.

		Scenarios	Description
FPDs as post-treatment	1	Current treatment systems (septic tanks/WWTPs) + post-treatment of sludge and WWTP effluents by FPDs	- sludge from septic tanks and WWTPs is collected by trucks and treated by FPDs - effluents from WWTP are treated by FPDs
	2	100% collection and treatment in WWTPs + post-treatment by FPDs	- sludge from WWPTs is treated by the FPDs - effluents from WWPTs are treated by the FPDs
FPDs as alternative treatment	3	50% collection and treatment in FPDs, 50% in WWTPs	50% of the wastewater is directly recycled through the FPDs, 50% is treated in WWTPs
	4	100% collection and treatment in FPDs	100% of the wastewater is directly recycled through the FPDs (total potential)

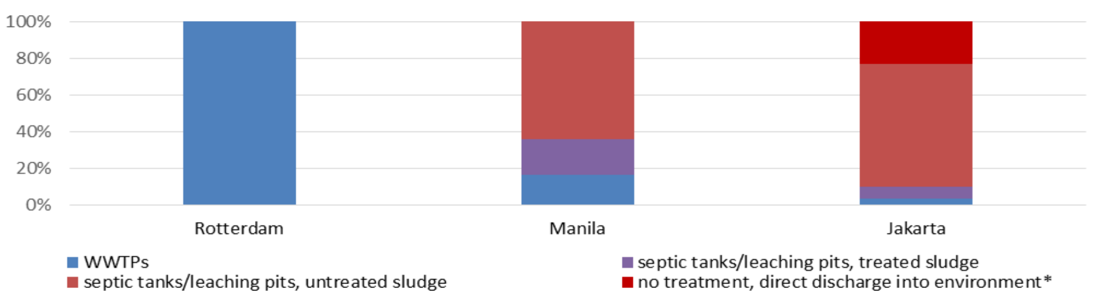

Figure 2 Sewage management overview for Rotterdam, Manila and Jakarta. (*Direct discharge includes pit latrines/toilets that discharge directly into ditches and drains and also the toilet waste from the population that doesn't have any facility).

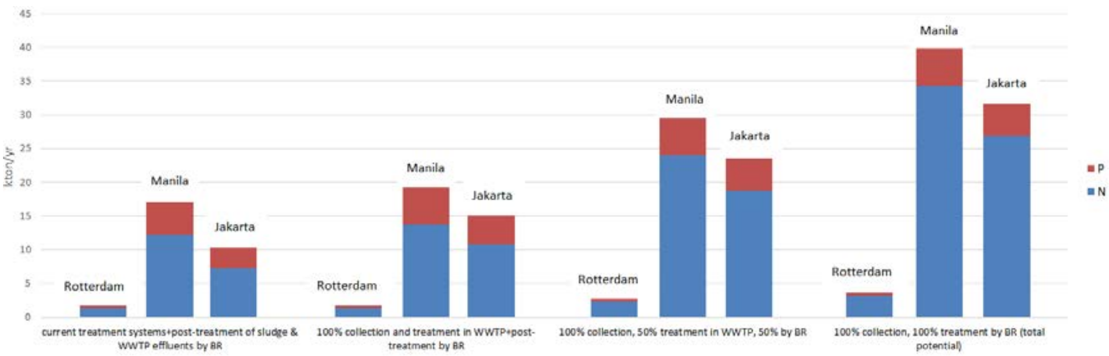

Figure 3 Comparison among P and N available in household wastewater for each scenario in Rotterdam, Manila and Jakarta.

Algae biomass production

Algae can be grown in floating productive developments using the waste nutrients and CO_2 that are produced in cities. 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 used as building block 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, 2009). 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, 2010). The protein content of algae biomass varies from 10% to 70%, with an average of 40%, comparable to meat and soy (Gouveia, 2008). Because of their wellbalanced 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, 2012) and higher suitability for contained growth. In addition, microalgae take up nitrogen faster than macroalgae (Sharif Hossain, 2008) which makes microalgae an interesting option for nutrients removal from surface water and wastewater. To determine the space requirements of algae a biomass yield of 20 g/m²/day was assumed. This value refers to “the best long-term productivities which have been attained in outdoor raceway ponds” (Borowitzka, 2013). Open raceway ponds were used as cultivation systems for the calculation. Open pond systems offer advantages compared to closed photobioreactor systems in terms of energy input and ease of operation. Recent work (Mooij, 2013) has shown that one of the main disadvantages of open pond systems, contamination by less productive species, can be overcome by creating a selective environment. The energy-input of the microalgal cultivation was assumed to be covered by renewable resources, such as wind- or tidal power. Algae yield was based on a global composition formula of an 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 chosen to maximize algae productivity instead of lipid yield.

Fish and vegetables yields in aquaponics

From the algal biomass, feed and biofuel yields were estimated. In this research it was assumed that proteins and part of the lipids from algae were used as fish feed. Fish could be farmed in aquaculture systems, but also in combination with vegetable production in in aquaponics systems. Aquaponics is based on a closed loop of nutrients: nutrients enter the system as fish feed, are then excreted, processed by bacteria and finally supplied to vegetables as fertilizer. The calculation estimates fish yields in aquaponics, based on the amount of available algae feed. The aquaponic system uses algae and offal from processed fish, grown within the system, as feed. It is assumed that offal is 25% of the fish weight. Lipids are provided by feeding part of the unprocessed algae biomass directly to the fish. Fish feed consists of 6% unprocessed algae, 79% algae cake after lipid extraction and 15% fish offal. The selected fish is tilapia, a common variety grown in aquaculture systems. Aquaponics is 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 ratio varies from 40 to 50 g/m²/day for leafy vegetables and from 50 to 80 g/m²/day for fruiting ones (Somerville, 2014). Based on the space that is available for plants production, total vegetables yield were calculated for cucumber, tomato and basil.

Biofuel yields

Biofuel yields are estimated from microalgae with 30% of lipids. For the conversion from lipids to oil, the specific gravity of algae oil coefficient is applied, which is equal to 0.85 kg/l (Sudhakar, 2012).

Land shortage estimation

Land shortage expresses the amount of space that a given population requires to sustain their current lifestyle, compared to the area that is available. Most of the space that cities require for food production is located outside of the city borders, but this space cannot simply be deemed deficient. The paper estimates the amount of food production space that is required by Rotterdam, Manila and Jakarta, based on FAOSTAT data on food supply per country and global agricultural land. The area for vegetal calories, is calculated from the total agricultural area, excluding “Permanent meadows and pastures”. Since 1/3 of crops are used as animal feed, the area for vegetal calories for human consumption is 15.5*2/3=10.3 million km^2. The area necessary to produce animal calories is therefore 33.6+15.5*1/3=38.8 million km^2 (“permanent meadows and pastures” and area for feed production). Efficiency of meat and vegetal products is estimated on a global scale and, according to food supply data and urban population, space required for food production is calculated for each city.

Next to the food production space, agricultural emissions due to meat and vegetables production on land are estimated using data by Gerber (2013). The space required to ‘offset’ food production emissions is then added to the land shortage estimation. The contribution of floating productive developments in reducing land shortage is finally estimated, taking into account the amount of space that can be saved on land by producing part of the food supply on floating developments.

Results and Discussion

Results from the estimations are here reported for the three cities. Table 2 includes the comparison between the algae and aquaponics yields in Rotterdam, Manila and Jakarta for the two scenarios with the lowest and highest amount of recycled nutrients. Biofuel yield for Rotterdam ranges from 8,300 to 12,900 m^3/yr for the scenarios S1 and S4 respectively. For Manila yields in S1 and S4 are estimated around 80,800 and 167,300 m^3/yr, whereas for Jakarta yields are 47,100 and 143,900 m^3/yr circa. In scenario 4, CO_2 needed by algae to grow their biomass are over 75 kt/yr for Rotterdam, 970 kt/yr for Manila and 838 kt/yr for Jakarta. Those values are circa 1%, 5% and 10% of the carbon dioxide emissions by the electricity sector in Rotterdam, Manila and Jakarta.

Table 2 Comparison of yields from algae and aquaponics and FPDs space requirements in Rotterdam, Manila and Jakarta, according to scenarios 1 and 4 (S1 and S4 respectively).

		Rotterdam		**Manila**		**Jakarta**	
		S1	**S4**	**S1**	**S4**	**S1**	**S4**
Algae yields	Algae biomass, kt/yr	27	43	267	554	156	476
	Algae as feed, kt/yr	20	30	190	396	111	340
	Lipids, kt/yr	8	12	76	158	45	136
Aquaponics yields	Fish, kt/yr	10	16	99	205	58	176
	Vegetables, average, kt/yr	50	77	483	1000	281	860
Biofuel yield	Biofuel, m^3/yr	8,300	12,900	80,800	167,300	47,100	143,900
Space requirement	Algae, km^2	3.9	6.0	37.8	78	22,0	67.4
	Aquaponics, km^2	1.6	2.5	15.0	31	8.8	26.8
	Total (incl. water surface), km^2	11.0	17.0	105.6	219	61.6	188.4

This research shows direct impacts of floating productive developments on the resilience of Rotterdam, Manila and Jakarta. If 100% of the household nutrients are recycled in floating productive developments, aquaponics could provide over 24%, 18% and 20% of the vegetal products consumed in the three cities respectively. At the same time, 20%, 38% and 58% of the average protein consumption is supplied by local fish production in the cities. Fossil fuel emissions from circa 10,000 passenger vehicles can be prevented in Rotterdam. For Manila and Jakarta, biofuel from algae would avoid burning fossil fuel of 127,000 and 109,000 passenger vehicles respectively.

The surface that is needed to recycle all the estimated nutrients in floating productive developments is about 17 km² in Rotterdam, 219 km² in Manila and 188 km² in Jakarta. This estimation takes into account also the water surface between floating platforms. Results show that growing fish and vegetables in floating productive developments can help reducing coastal cities footprint by choosing for more efficient food production methods and producing local food. Over 3,800 km², 46,900 km² and 42,200 km² of land are saved globally when FPDs are built in Rotterdam, Manila and Jakarta. To put the number in perspective, the estimations are equal to 12, 73 and 57 times the area within the administrative boundaries of Rotterdam, Manila and Jakarta respectively. The estimation also takes into account the CO_2 sequestration space which is required to compensate for the carbon dioxide emissions caused by food production on land. CO_2 sequestration space that can be saved producing food and biofuel in FPDs in Rotterdam, Manila and Jakarta is equal to 1,500 km², 15,000 km² and 14,800 km² respectively.

The results take into account only nutrients from household wastewater. In reality other sources of nutrients are present within the cities. Taking them into account would increase the potential of FPDs. A study on the potential of FPDs for the Rotterdam City Region showed how surface water can be an important source of nutrients. For a more complete estimation of the potential amount of nutrients available, data on water quality need to be collected for each region.

Conclusions

The research has demonstrated how productive floating developments (FPDs) have the potential to provide a wide range of benefits to delta cities. Some benefits are local and directly experienced by cities: climate proof urban space, local food and biofuel production, and the creation of 'green jobs'. Other benefits have global implication, as for example recycling waste and CO_2 emissions, preventing nutrients pollution and reducing pressure on current fish stock. This article investigated the potential of productive floating developments in three delta cities, Manila, Jakarta and Rotterdam, to reduce land scarcity and use CO_2 and waste nutrients in a productive way. The results showed that FPDs can significantly reduce the global land area that cities require to sustain their current food and fuel consumption. To utilize the potential of FPDs, implementation in practice as well as further research on the efficiency and potential of FPDs 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 to integrate building and food production on water, demonstrating concepts that have not yet been applied in practice.

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