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HARVEST TO HARVEST: RECOVERING NITROGEN, PHOSPHORUS AND ORGANIC MATTER VIA NEW SANITATION SYSTEMS FOR REUSE IN URBAN AGRICULTURE

Rosanne Wielemaker[*1], Ingo Leusbrock[1], Jan Weijma[1,2], Grietje Zeeman[1,2]

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Abstract: To maintain the city as a viable concept for human dwelling on the long term, a circular metabolism needs to be adopted which relies on recovering, reusing and recycling resources, in which output ('waste') from one metabolic urban conversions equals input for another. Urban Agriculture (UA) and source-separation-based New Sanitation (NS) are gaining momentum as measures for urban resource management. UA aims to localize food provisioning while NS aims to reorganize wastewater and organic waste management to recover valuable and crucial resources. The objective of this research is to assess the match between the supply by NS systems and the demand from UA for nitrogen, phosphorus and organic matter, in terms of quantity and quality, to foster a circular metabolism. The research is contextualized in the city of Rotterdam. The methodology used is based on the Urban Harvest Approach (UHA), developed previously for the urban water cycle. Novel to this research is adapting the UHA to nitrogen, phosphorus and organic matter loads for two practiced UA typologies (ground-based and rooftop) and four NS concepts for the treatment of domestic urine, feces and kitchen waste. Results show that demand for nutrients and organic matter from UA can be minimized by 65-85% and a self-sufficiency of 100% for phosphorus can be achieved, while partial self-sufficiency for nitrogen and organic matter. This research reveals that integration of NS and UA maximizes urban self-sufficiency.

1. Introduction

Cities depend on regional and global hinterlands for the supply of water, energy, nutrients and materials and for the disposal of wastes (Brunner, 2007, Kennedy et al., 2007, Agudelo-Vera, 2012, Hodson et al., 2012), deeming cities hotspots for resource conversion. This conversion follows a linear chain of high quality resource inputs and low quality waste outputs (Figure 1a.). Few resources are currently recovered for reuse. This linear chain leads to two major challenges: first, cities' high rate of consumption puts stress on resource availability (e.g. phosphorus, fossil fuels), and second, the disposal of vast amounts of waste causes pollution (e.g. water and resource contamination, biodiversity loss, deforestation, and pollution in air, water and land). For example, cities currently import large quantities of food not only from their hinterlands, but also from locations across the globe. At the same time, they produce low or even negative value waste loads containing disposed and excreted nutrients. These are often mixed and collected via large-scale engineered infrastructures that endorse this linear tendency and make it difficult to effectively recover resources (Balkema et al., 2002, Hodson et al., 2012). With more than half of the world's population currently residing in cities, this linear tendency is further intensified (United Nations, 2014).

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[*] Corresponding author, rosanne.wielemaker@wur.nl

[1] Sub-department of Environmental Technology (Wageningen UR), rosanne.wielemaker@wur.nl, ingo.leusbrock@wur.nl

[2] LeAF, an independent research and consultancy organization focused on the development and implementation of knowledge, expertise and technologies in treatment and valorization of organic residues. grietje.zeeman@wur.nl, jan.weijma@wur.nl

As hot-spots of resource conversion, however, cities also present an excellent opportunity to adopt a circular metabolism for these resources, in which output (‘waste’) from one process equals input for another. As opposed to the current linear urban metabolism, a circular urban metabolism aims to recover and reuse (recycle) resources within or between urban functions to reduce the external input of virgin resources and the output of waste (Agudelo-Vera et al., 2012) (Figure 1b). To move towards a circular urban metabolism, resource input-output flows of urban functions need to be identified, described and matched in terms of quantity and quality. New Sanitation and Urban Agriculture are currently gaining global interest individually as measures to improve urban resource management (Mougeot, 2006, Food and Agriculture Organization of the United Nations, 2014). Two urban functions that could be matched for mutual benefit.

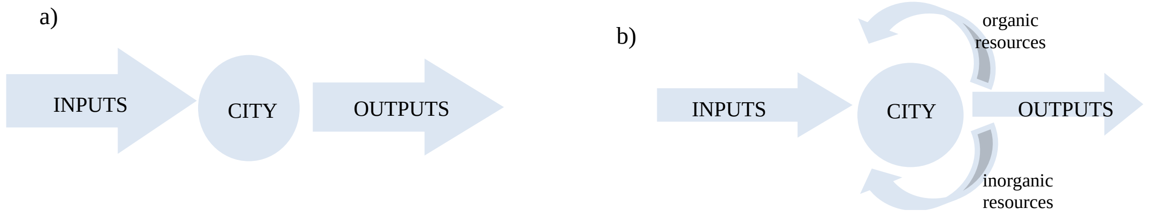


Figure 1. a) A linear metabolism of inputs and outputs. b) A circular metabolism reuses, recycles and recovers resources from urban waste streams, reducing resource inputs and outputs.

Urban agriculture (UA) is the *local* production of food within (peri-)urban areas, which in addition fosters education, employment, place-making, community building and/or closing organic resource cycles (Mougeot, 2000, Smit et al., 2001). UA assimilates a wide variety of activities, locations, scales, purposes and engagement (e.g. community gardens, roof-top farming, commercial farming and animal husbandry). UA involves intensive cultivation/breeding methods that yield a diverse selection of flora and fauna, and integrates it with the local urban economic, social and ecological systems. New sanitation (NS) systems manage the collection, transport, treatment, and recovery of solid waste and wastewater streams (e.g. urine deviated vacuum toilets, anaerobic digesters, struvite precipitation) with the aim to recover resources at local scales (i.e. water, nutrients, organic matter, energy), increasing efficiency, reducing energy costs, and/or offering local solutions to waste management (Lens et al., 2001, Kujawa-Roeleveld and Zeeman, 2006, Zeeman, 2012). NS systems often include source separation of waste and wastewater streams (e.g. black water (urine and feces) and grey water (shower, sink, laundry)).

Re-establishing a partnership between agriculture and sanitation is not a new phenomenon. Various studies have looked at the possible connection between sanitation and crop production including: wastewater reuse/irrigation for crop production (Smit and Nasr, 1992, Strauss, 2001, Beuchler et al., 2006), treatment, recovery and reuse of fertilizers from wastewater (Lens et al., 2001, Jenkins, 2005, Mihelcic et al., 2011, Tervahauta et al., 2013), reuse of urine (Maurer et al., 2003, Maurer et al., 2006), bioavailability of recovered products to crops (Jönsson et al., 2004, Oenema et al., 2012), guidelines on urine and feces reuse in agriculture to ensure safe handling (Jönsson et al., 2004, Heinonen-Tanski and van Wijk-Sijbesma, 2005), risks of micro-pollutants, pathogens and heavy metals (Heinonen-Tanski and van Wijk-Sijbesma, 2005, Winker et al., 2009, Tervahauta, 2014), and the link between urban agriculture and sanitation systems as an economic and food security measure in developing countries (Streiffeler, 2001, Kone, 2010, Cofie et al., 2013).

However, the feasibility to match input and output flows between UA and NS systems should not be overlooked. To start, data on the quantity and quality of the input demands from UA systems is lacking, as UA is for the most part unregulated. Second, data on the quantity and quality of the products produced by NS systems has, and continues to be, researched (Lens et al., 2001, Zeeman and Kujawa-Roeleveld, 2011, Tervahauta et al., 2013). However, the extent of their reuse in UA is uncertain (e.g. fertilizer quantity in terms of slow release vs quick release, or contaminants). To match resource flows and fine-tune both UA and NS systems, these values need to be uncovered.

1.1 Scope of Research and Research Objectives

The scope of this research focuses on the recovery of nitrogen (N), phosphorus (P) and organic matter (OM) from domestic wastewater and kitchen waste to determine the extent to which these resources can cover the demand from UA, in Rotterdam, the Netherlands. The reason for this focus is three-fold. First, the global concern regarding resource depletion and environmental pollution due to current consumption and disposal of nutrients, N and P, and OM. Second is the increased regional interest in the Netherlands for the professionalization of UA and the recovery of resources from waste streams. Third is Rotterdam's interest in improving local resource management and implementing UA.

The overall goal of this paper is to model combined UA and NS systems to evaluate the degree to which N, P and OM input-output flows can be matched and quantify the degree of self-sufficiency. This will be done in three steps: a) select and characterize relevant UA typologies and quantify the demand of nutrients and organic matter for each selected typology, b) select the NS technologies (proven at lab and pilot scale) most appropriate for the recovery nutrients from residual waste streams and quantify the harvested nutrients and organic matter, c) quantify the extent to which the demand for nutrients from UA can be met by recovered nutrients from the selected NS systems.

1.2 Methodological Framework: Urban Harvest Approach

The methodology used in this research is an adaptation of the Urban Harvest Approach (UHA) developed at the Sub-department of Environmental Technology (ETE) at Wageningen UR. It has been most extensively applied to the urban water cycle to improve urban resource management towards self-sufficiency by applying three management strategies: demand minimization, output minimization (by resource cascading, recycling and recovery), and multi-sourcing (Agudelo-Vera et al., 2012, Agudelo-Vera, 2012). In this research, these strategies are shown in Figure 2 and are defined as follows:

- *Step 0: Baseline Assessment:* This describes the existing situation, including demand inventory and current technologies. Here the baseline identifies the quantity and type of nutrient input demand for each UA typology, and the output of nutrient flows from domestic sanitation waste flows.
- *Step 1: Demand minimization:* This strategy reduces the demand for nutrients via the implementation of new technologies or via changes in human behavior. Here the demand for N, P and OM fertilizer can be reduced by using different farming technologies or by reducing fertilizer application or patterns.
- *Step 2: Output minimization:* This strategy minimizes outputs via three strategies: cascading (direct use of outputs for a purpose with lower quality demand), recycling (the reuse of a resource flow after a quality upgrade, which generally costs energy) and/or recovery (the extraction of valuable resources from waste streams) from the outputs. Cascading will not be used because primary and/or secondary treatment of human excreta is needed to secure the removal of pathogens (Jönsson et al., 2004).

- *Step 3: Multi-sourcing:* Satisfying the remaining demand by harvesting local, renewable resources. Multi-sourcing will not be included in this research as there are few renewable sources of N, P and OM.

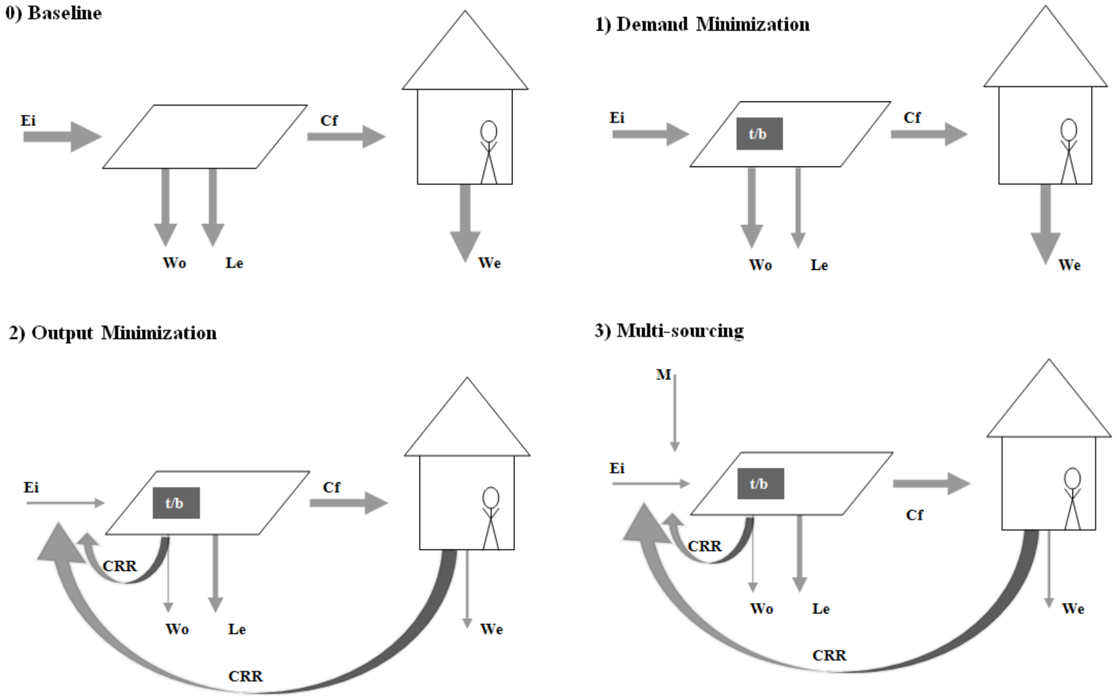


Figure 2. Schematic of the UHA adapted to flows between urban agriculture and new sanitation. Ei= External input, Wo= Waste agriculture exported, Le= Losses environment, Cf= Consumed food, We=Waste exported via sanitation, t/b= technology and behavioural changes, CRR= Cascading, recycling and recovery (harvesting strategies), M= Multi-sourcing

This research uses the UHA to match N, P and OM flows between selected UA typologies and NS concepts for the treatment of domestic urine, feces and kitchen waste (described later). The designed systems are evaluated using the indices developed by Agudelo-Vera et al. (2012), including: Demand Minimization Index (DMI and Self-Sufficiency Index (SSI).

Demand Minimization Index (DMI): The DMI describes the change in demand in reference to the baseline demand. Baseline demand (D_o) reflects the current resource demand (status quo) from UA and the minimized demand (D) describes the demand adjusted to reflect equilibrium fertilization values. A DMI of 0 indicates that no demand minimization has taken place. The DMI is calculated using Equation 1.

$$DMI = \frac{Baseline\ demand\ (D_o) - Minimized\ demand\ (D)}{Baseline\ demand\ (D_o)} * 100$$

Self-Sufficiency Index (SSI): The SSI is a measure of the self-sufficiency of a system: in this case, to what extent can nutrients from NS systems provide sufficient nutrients to fulfill the demand from UA. The SSI is measured by the resources harvested and reused (Rr) against the minimized demand (D). The SSI is calculated using **Equation 2.**

$$SSI = \frac{Resources\ reused\ (Rr)}{Minimized\ demand\ (D)} * 100$$

2. Urban Agriculture Typologies and New Sanitation Concepts

2.1 Urban Agriculture and the Selected Typologies

UA is diverse in form and purpose, which for this study requires that UA typologies be clearly defined to identify respective input and output flows. The nutrient demand for each typology is dependent on various factors including nutrient retention, nutrient extraction, precipitation, individual plant demand, and soil type. In addition, different plants have varying demands. For example, lettuce may require 165-180kg/ha of nitrogen, while chicory may only need 100kgN/ha, and cauliflower up to 210-230kgN/ha (Rijksoverheid, 2014a). The soil pH also influences the availability of nutrients to plants, for example, the maximum availability of phosphorus occurs in the 6.0-7.0 pH range (College of Agricultural Sciences, 2014).

Two UA typologies were selected and defined, namely, ground-based urban agriculture (ground-based UA) and rooftop urban agriculture (rooftop UA). These were selected because both ground-based and rooftop UA initiatives can be found in Rotterdam, which could serve as reference case-studies for this research. Ground-based UA grows edible plants at ground level in soil (e.g. Small Plot Intensive (SPIN) farming, community gardens/farms, permaculture farms and forest gardening)

Rooftop UA involves cultivating crops on the rooftops of urban buildings, usually flat roofs that are most suited to carry additional weight. This typology can cultivate plants in soil or in a soil-like substrate. The benefit of this typology is similar to that of green roofs: building insulation, urban cooling effect, water retention, etc. A rooftop’s appropriateness for urban farming depends on the height and capacity to sustain weight. High rooftops are exposed to strong winds and may be limited in the kinds of crop varieties, while the building needs to be strong and be able to hold between 60-150kg/m^2 of additional weight. (Dumitrescu, 2013).

2.2 New Sanitation and the Selected Concepts

Sanitation is the promotion of hygiene via the management and treatment of wastes, including the physical and organizational structure (Brikké and Bredero, 2003, Mihelcic et al., 2011). Sanitation systems in developed countries are mostly centralized: extensive networks for the collection and transport of mixed and diluted waste streams, treated at one central point, with little intention to recover valuable resources (Wilderer and Schreff, 2000). These are contrasted with decentralized systems: stand-alone systems used for treating more concentrated waste streams sourced from smaller areas either on-site or close to the point of generation (Wilderer and Schreff, 2000, Tchobanoglous and Leverenz, 2013).

NS is a new paradigm for the collection, transport, treatment, and recovery of solid waste and wastewater that aims to reconfigure waste management at local scales: recovering resources, increasing efficiency, reducing energy consumption and improving health and environmental protection (Lens et al., 2001, Kujawa-Roeleveld and Zeeman, 2006, Zeeman, 2012, Tervahauta et al., 2013). NS systems are local systems (source, recovery and reuse are in close proximity) and the technical design completely serves the above aim. The design often includes source separation of waste and wastewater streams, collecting black water (urine and feces), grey water (shower/bath, sink, laundry, dish washer) and/or urine separately. The different types of streams are outlined in Table 1. Depending on the types of streams separated and the local context, NS concepts can be configured for treatment and recovery to achieve reuse or discharge parameters.

Table 1. Wastewater sub-streams and their sources

Stream	Sub-stream	Source
Black water	Yellow water	Urine, with or without water
	Brown water	Feces and toilet paper, with or without water
Greywater	Light grey water	Shower, bathtub, bathroom basin
	Dark grey water	Kitchen sink, dishwasher, washing machine

For the recovery of nutrients, urine, feces and kitchen waste are the most promising streams for this research since they have the highest load of N, P, and OM (measured as COD), as shown in Figure 3. It is noted that urine contains most N and P, followed by feces. Feces and kitchen waste contain most organic matter, suitable for making compost and soil conditioners. Therefore, urine, feces, black water (BW) and kitchen waste (KW) were used in this research, while greywater (GW) was not considered.

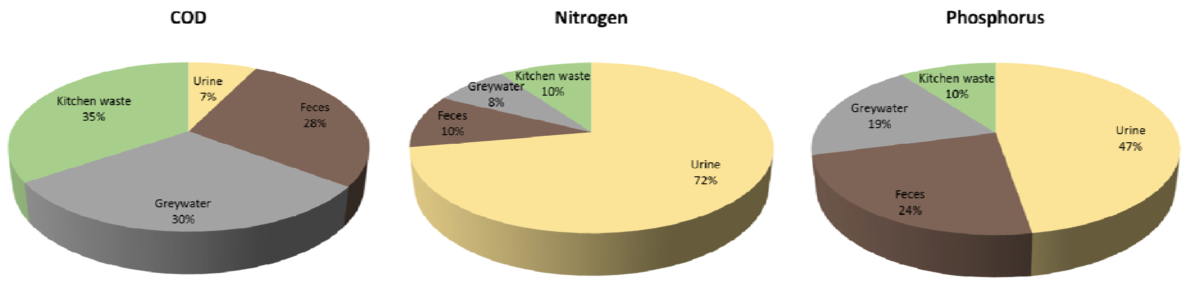


Figure 3. Distribution of nitrogen, phosphorus and organic matter (COD) across domestic waste and wastewater streams (Refer to Table 4 for numbered values)

New Sanitation systems can be divided into subsequent sub-systems, from collection to reuse/disposal/discharge. These sub-systems are described below, specifically with reference to NS (Maurer et al., 2012):

- *User interface/collection:* the user access to the sanitation system, usually via the toilet. For example, low flush and vacuum toilets, urine-diverting toilet and composting toilets.
- *Conveyance and transportation*: the transport of the waste streams from one sub-system to the other, for example via human powered or motorized pathways.
- *Storage and treatment:* the collected waste streams are stored and/or treated, requiring appropriate technologies and facilities. For example, urine storage, composting kitchen waste, anaerobic treatment (ie. up-flow anaerobic sludge blanket (UASB) reactor), nitrification and denitrification (ie. oxygen limited anaerobic nitrification denitrification (OLAND) and disinfection.
- *Recovery*: the harvesting of resources from waste streams such as water, metals or nutrients. Struvite recovery, using a struvite precipitation reactor, from urine and black water is used for the recovery of P and N.
- *Reuse/disposal:* the use of recovered and treated products from prior sub-processes in which resources are returned to the ecological or anthropogenic environment.

The configuration of technologies across the sub-processes determines the extent to which resources can be recovered, in terms of quantity and quality. For example, removal efficiencies, methanization levels, and precipitation efficiencies influence the amount of nutrients that can be harvested and the quality of the product for human and environmental hygiene.

3. Results

3.1 Baseline Nutrient and Organic Matter Demand, and Demand Minimization

The nutrient demand was calculated for each typology (kg/ha) by comparing data from primary and secondary sources, including interviews with present urban farmers in Rotterdam, - the actual amount of fertilizer applied- as well as fertilizer regulations for conventional agriculture in the Netherlands, and values for equilibrium fertilization – the advised amount of fertilizers -, as further described in the following sections.

3.1.1 Ground-based Urban Agriculture

The baseline demand for ground-based UA was gathered from interviews with an UA farm in Rotterdam and the fertilization regime they follow. This fertilization regime included the use of both slow release and quick release fertilizers distributed in a compost mixture, chicken manure, and a liquid fertilizer. Table 2 compares the baseline demand with conventional norms and regulations for N and P use in the Netherlands and with equilibrium fertilization values. The conventional norms and the equilibrium fertilization values were averaged from 22 different types of horticultural crops (Fink et al., 1999, Rijksoverheid, 2014b, Rijksoverheid, 2014a). Equilibrium fertilization reflects the nutrients contained in the total harvested fresh matter (harvest residues and marketable yield) assuming an optimal yield per hectare (Fink et al., 1999). These values were used because it reflects what a plant actually takes up, as opposed to the conventional regulations for fertilization in the Netherlands.

Table 2. Annual Nutrient Demand Ground-Based Urban Agriculture

Source	**N available* (kg/ha)**	**P_2O_5 available* (kg/ha)**	**Organic matter[4] (kg/ha)**
Baseline Demand[1] (D_o)	109.3	217.3	7861
Conventional norms[2]	178.3	65	-
Equilibrium fertilization[3]	202.7	32.2	-
Minimized Demand (D)	**109**	**32.2**	**2685**

[1] Table on fertilizer advice (Van Ierssel, 2013)

[2] Averages calculated from nitrogen and phosphorus use norms and regulations (Rijksoverheid, 2014a, Rijksoverheid, 2014b).

[3] Averages calculated from data on fertilizer recommendations and nutrient balances (Fink et al., 1999)

[4] OM=32% of dry matter. From: Samenstelling en werking van organische meststoffen (de Haan and van Geel, 2013).

[*] Nutrient values for nitrogen and phosphorus are usually expressed by weight of N and P_2O_5. The actual phosphorus content, however, is then 44% of the P_2O_5 value. Nitrogen is simply expressed as elemental N or mineral nitrogen, Nmin. Both N and P_2O_5 are calculated using the “werkings coefficient” for compost and animal manure. N available is 10% in compost and 55% from chicken manure. P available is 50% in compost with a maximum of 3.5g P_2O_5/kg dry matter of compost

Noticeable from Table 2 is that for P the baseline demand exceeds the conventional norms by a factor 3 and the equilibrium fertilization values by even a factor 7, meaning strong over fertilization is taking place. The equilibrium values were used as the minimized demand assuming an ideal scenario in which the fertilization regime could reflect the amount of nutrients that crops take up, and not more. Over fertilizing results in either increased nutrients in the soil or their release to the environment. The baseline demand was used when it was below the equilibrium fertilization value, as is the case with N for ground-based UA. OM was minimized to reflect that contained in 15,000 kg of compost as suggested in literature (Goed boeren in kleinschalig landschap, 2011).

The DMI is then calculated using Equation 1. For ground-based UA the DMI for N is 0, for P is 85% and for OM is 66%. The N demand does not need to be minimized because it lies well below the equilibrium fertilization value. The amount of P and OM minimized for this typology is significant and highlights the degree of over-fertilization, especially of P, a finite resource (Cordell et al., 2009).

3.1.2 Rooftop Urban Agriculture

The baseline demand for rooftop UA was gathered from a rooftop UA farm in Rotterdam that used a growing substrate and drainage system that is light in weight to adhere to the 180kg/m^2 capacity of the roof. The substrate is low in organic matter to make it as light as possible, and therefore no compost is added in their fertilization regime, but rather slow release granulates. No quick release fertilizers are used. The N, P and OM values for the baseline demand are shown in Table 3, in comparison to the conventional norms and the equilibrium fertilization values. Again, the equilibrium fertilization values were assumed for the minimized demand, except in the instances that the baseline demand was below these values.

For rooftop UA the N demand is below the equilibrium fertilization value, meaning that minimization is not needed. OM is kept as the baseline demand. For P, however, the DMI (Equation 1) is 65%, meaning that the demand is minimized significantly.

Table 3. Nutrient Demand rooftop Urban Agriculture

Source	**N available* (kg/ha)**	**P_2O_5 available* (kg/ha)**	**Organic matter (kg/ha)**
Baseline Demand[1] (D_o)	112.5	92.3	1742.5
Conventional norms[2]	178.3	65	-
Equilibrium fertilization[3]	202.7	32.2	-
Minimized Demand (D)	**112**	**32.2**	**1742.5**

[1] Calculated from: Technische Fiche ECO-MIX 1 (DCM Nederland BV, 2014) and Organische Gedroogde Koemest (Humuforte, 2014)

[2, 3, 4] Same as in **Table 2**

[*] calculated using the “werkingscoefficient” for compost and animal manure. N available is 40% in purchased grass-fed animal-derived fertilizers

3.2 Baseline Nutrient and Organic Matter Supply from Waste and Wastewater

Rotterdam, with an area of 319.35 km^2, has a population of approximately 620,000 people (Gemeente Rotterdam, 2013). There are a total of 317,549 households in the city housing approximately 1.94 individuals per household (Gemeente Rotterdam, 2013). The city produces a total of 76,000 tons of household organic solid waste. However, most of this organic solid waste is collected together with municipal solid waste and incinerated for the generation of energy. A smaller fraction, 1% of household organic solid waste, called “groente, fruit en tuin (GFT) afval” is collected separately at source, composted and sold via a third party to the agricultural sector.

The city's wastewater is managed and treated by the Waterschap Hollandse Delta and Hoogheemraadschap Schielanden en Krimpenerwaard. Using Table 4, the loads of the nutrients can be calculated for the whole population of Rotterdam. Household black water and kitchen waste generated daily represent a load of 1,356 kg of P and 316,850 kg of N. OM is 32% of the total dry matter, which is 88,764 kg per day. Using NS systems, these nutrients and OM are recovered with a respective efficiencies.

Table 4. Mean compositions of urine, feces, black water and kitchen waste calculated based on European data as reported in literature, including respective standard deviations (Kujawa-Roeleveld and Zeeman, 2006, Magid et al., 2006, Daigger, 2009, Friedler et al., 2013, Tervahauta et al., 2013)

Parameter	unit	Urine	s.d.	Feces	s.d.	Kitchen waste	s.d.	total
Volume	L/p/d	1.3	0.12	0.13	0.06	0.2	0.00	86.83
COD	g/p/d	12.5	1.91	47.9	12.23	59	0.00	171.10
Dry matter	g/p/d	46.5	16.26	35.5	7.78	75		211.80
TN	g/p/d	10.2	1.10	1.4	0.38	1.4	0.52	14.10
TP	g/p/d	1.1	0.34	0.5	0.05	0.2	0.06	2.20
K	g/p/d	2.6	0.15	1	0.09	0.3	0.12	4.50

3.3 Output Minimization

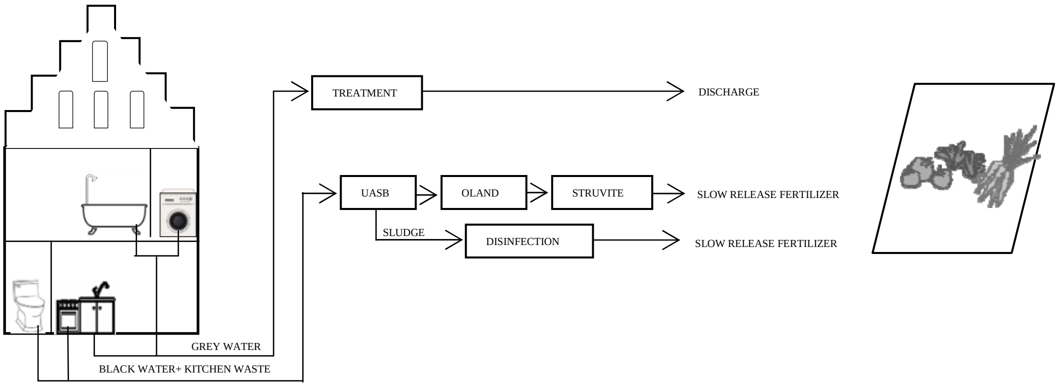
3.3.1 New Sanitation Concepts 1-4

In Rotterdam the collection sub-system widely used for urine and feces is still the standard flush toilet. The low flush, vacuum toilet and urine-diverting toilet are currently the only proven technologies for the collection of concentrated black water. The collection system, or rather the composition(s) of the stream(s) collected, then influences the proceeding treatment steps possible.

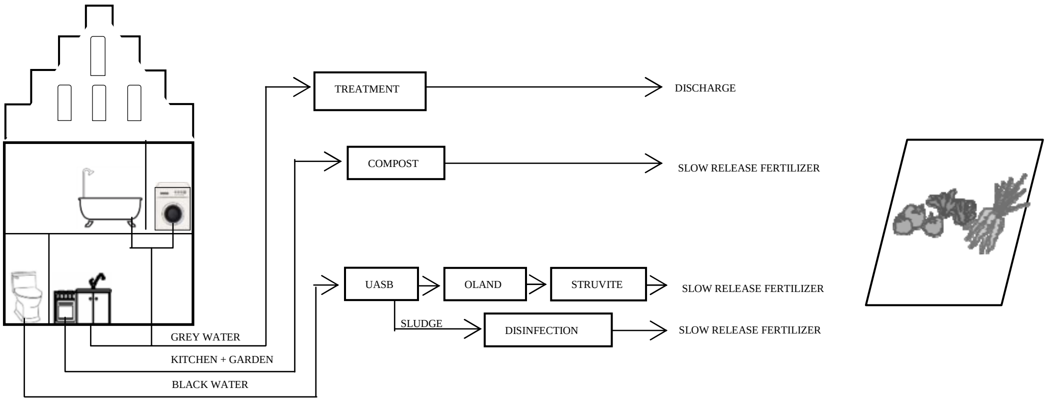
The recovery/reuse sub-systems need to provide at least similar comfort compared to current sanitation systems, produce little nuisance (odors), and have to be included into the current urban fabric taking up relatively little space. This study is concerned with the recovery of resources, and therefore, post-recovery treatment steps are not further outlined or quantified. The source separated streams of interest include urine, feces, and kitchen waste, and the combination of these.

Four NS concepts (Figure 4) were selected based on systems demonstrated on lab and pilot scale, separating urine, feces, black water and/or kitchen waste with respective treatment systems. Concept 1 includes source-separation of black water combined with kitchen waste and is based on the system in place in Sneek, the Netherlands separating GW from BW and KW (grinded), (Waterschoon, 2011, Tervahauta et al., 2013). The BW and KW are treated anaerobically in an UASB reactor, followed by an OLAND reactor and struvite precipitation. Concept 2 includes the same treatment steps as Concept 1 with the exception of KW, which is collected separately for composting (Fricke and Vogtmann, 1994, Eklind and Kirchmann, 2000, Hargreaves et al., 2008, Dekker et al., 2010). Concept 3 is similar to Concept 1 with the exception of urine, which is collected separately and stored (Jönsson et al., 1998, Jönsson et al., 2004, Maurer et al., 2006). Concept 4 separates KW for compost and urine for storage (a) or struvite precipitation (b). Feces join the GW.

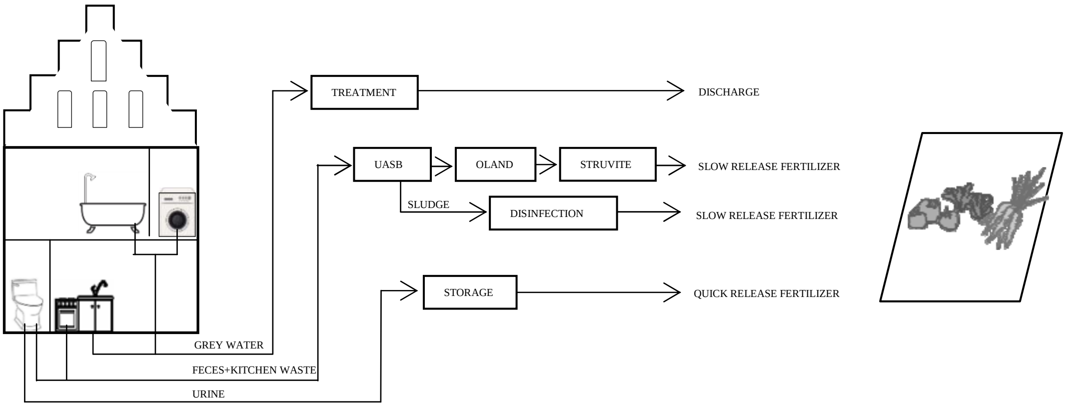
Concept 1



Concept 2



Concept 3



Concept 4

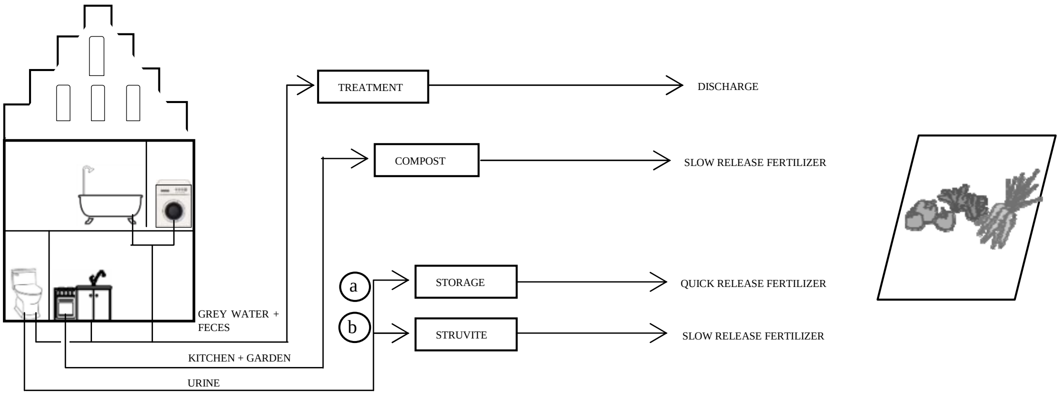


Figure 4. New Sanitation concepts, including sub-streams and recovery technologies

In Concepts 3 and 4, urine is separated at source via a urine-diverting toilet using 0.2L of water per flush. This concentrated stream is stored in Concept 3 and 4a and undergoes struvite precipitation in Concept 4b. The separated urine in Concept 3 does not undergo struvite precipitation because the treatment of the feces and KW stream already includes a struvite precipitation step.

3.3.2 Combined Urban Agriculture and New Sanitation

The demand for N, P and OM from each UA typology was compared with the supply generated by each NS concept. In total eight combinations were evaluated for the degree of self-sufficiency. However, for the evaluation of possible UA and NS combinations, both self-sufficiency (SSI) and the number of persons needed to provide that SSI is relevant. While a high SSI is preferable for the sourcing of local resources, the efficiency of the NS concept also reflects the potential to implement the NS concepts requiring the least amount of individuals. Figure 5 show the SSI for each combination.

The scenarios coupling ground-based UA with NS concept 3 and 4a provide 100% self-sufficiency of P. System 4a, however requires 10 times as many persons/ha, meaning that to fertilize the available 2363 ha almost the entire city of Rotterdam (94%) would need to be connected to NS systems. Moreover, due to the topography of the city (high rises), the collection of GFT from 94% of the city’s inhabitants is not realistic. The other scenarios fail to supply the quick release demand for P and N. Therefore, ground-based UA and concept 3 provides the best combination.

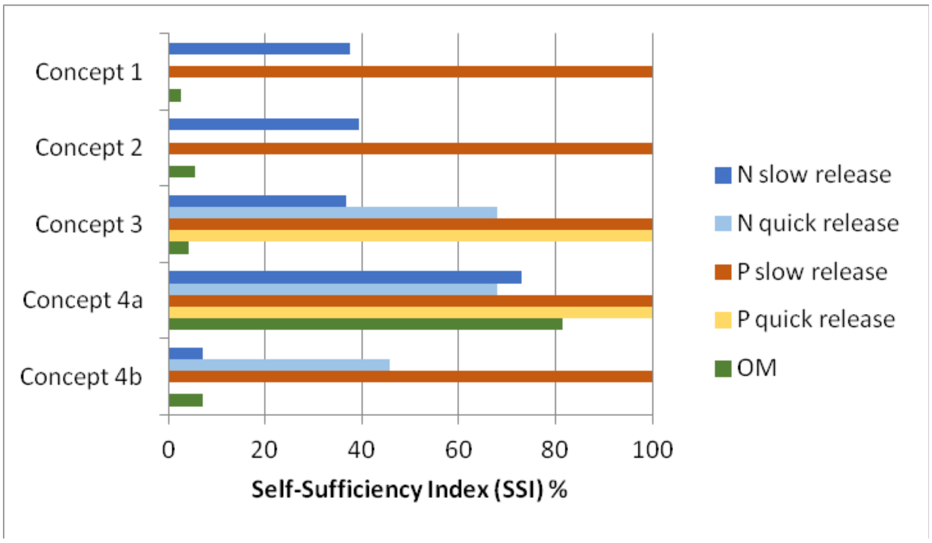


Figure 5. Self-Sufficiency in N, P and OM for Ground-based UA and NS concepts

Rooftop UA, as identified in section 3.1.2

Noticeable from Table 2 is that for P the baseline demand exceeds the conventional norms by a factor 3 and the equilibrium fertilization values by even a factor 7, meaning strong over fertilization is taking place. The equilibrium values were used as the minimized demand assuming an ideal scenario in which the fertilization regime could reflect the amount of nutrients that crops take up, and not more. Over fertilizing results in either increased nutrients in the soil or their release to the environment. The baseline demand was used when it was below the equilibrium fertilization value,

as is the case with N for ground-based UA. OM was minimized to reflect that contained in 15,000 kg of compost as suggested in literature (Goed boeren in kleinschalig landschap, 2011).
The DMI is then calculated using Equation 1. For ground-based UA the DMI for N is 0, for P is 85% and for OM is 66%. The N demand does not need to be minimized because it lies well below the equilibrium fertilization value. The amount of P and OM minimized for this typology is significant and highlights the degree of over-fertilization, especially of P, a finite resource (Cordell et al., 2009).

Rooftop Urban Agriculture, does not have a demand for quick release fertilizer. Therefore the SSI for both quick release N and P is not applicable, even though Concepts 3 and 4a produce quick release N and P from urine. The SSI for scenarios coupling rooftop UA with the NS concepts are low for slow release N and OM. The scenario combining rooftop UA with Concept 4b is the most self-sufficient for N and P, although Concept 4a is most self-sufficient for OM, compared to the other combinations. To produce enough compost for the 906ha of rooftop area appropriate for UA, household organic solid waste needs to be collected from 40,500 inhabitants, a mere 6.5% of the population of Rotterdam. This is realistic considering that Rotterdam is striving to collect 6% by 2018 anyway. Following Concept 4b, Concept 2 would best be combined with rooftop UA of slightly lower SSI but requiring only 26.8 p/ha (less intervention than Concept 4a).

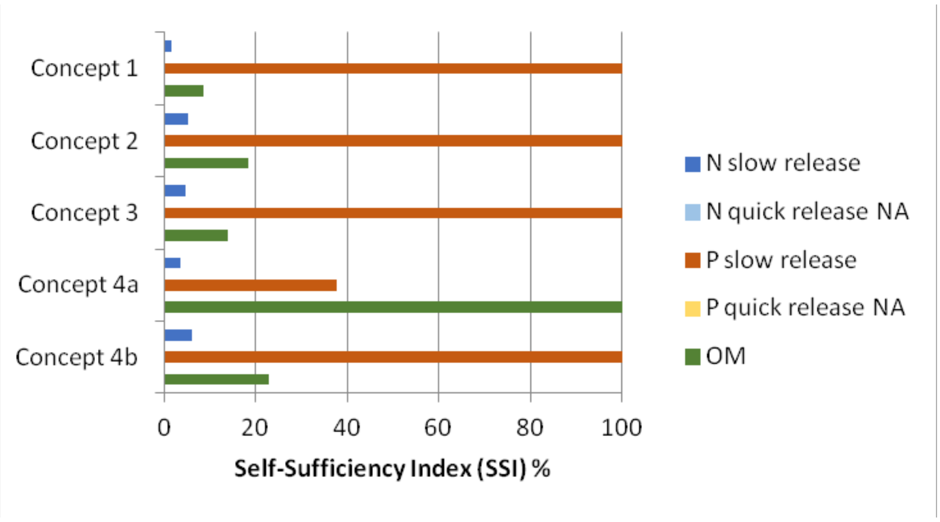


Figure 6. Self-Sufficiency in N, P and OM for Rooftop UA and NS concepts

4. Discussion and Conclusion

The UHA offers a step-by-step methodology to gain insight into the opportunities that lie in integrating urban agriculture and new sanitation. However, its application to N, P and OM input-output flows presented challenges at each step of the methodology.

4.1 Baseline Demand

The baseline N, P and OM demand from urban agriculture was based on two existing urban agriculture initiatives in Rotterdam. While their demand was actual, they are not telling for fertilizer regimes of all UA initiatives within those typologies. Different reference studies would have provided different data on baseline demand, in terms of quantity but also fertilizer type (ie. slow release vs quick release).

In this research, both fertilization regimes showed over-fertilization of P. Considering that conventional agriculture in the Netherlands is heavily regulated in their N and P use to reduce pollution of water resources, and that P is a finite resource of increasing scarcity, urban agriculture fertilization regimes should also take measures to prevent over-fertilization and the mismanagement of N, P and OM. For instance, regulations could be formulated for UA, although the range of UA typologies requires a more context specific tool to help initiatives make substance flow analyses. In addition, UA also changes the nutrient loads discharged to the urban water cycle, such as the increase of nutrient loads to the sewer system via rooftop UA. Therefore, expanding urban agriculture across cities has various implications for urban resource cycles.

4.2 Demand Minimization

Minimizing the demand for N, P and OM from urban agriculture is achieved by behavioral changes, simply by administering less of these resources to equilibrium fertilization values. While this is a novel point of departure for the application of nutrients, further research is needed to identify the optimal fertilization regime for each UA typology, considering that nutrients mineralize in the soil and runoff may occur. Here UA pilot studies should be open to monitoring, collecting and sharing data. In addition, technological options for the administration of fertilizers that minimize the demand (ie. injection fertilization at the plant base as opposed to sprinkler systems) were not considered in this research. These technological changes could administer fertilizers where and when the plant needs it, and thereby minimize the demand.

4.3 Output Minimization

The harvested N, P and OM from the new sanitation concepts were found in stored urine, GFT compost, struvite and disinfected sludge. The selection of the concepts was based on lab and pilot scale technologies and data. For ground-based UA, Concept 3 and 4a provided a SSI for P of 100% with both slow and quick release fertilizers. For rooftop UA, most concepts could provide a SSI for P of 100% because the typology only had a demand for slow release fertilizer. Again, this reflected the reference case study selected and not a definitive fertilization regime for these UA typologies. Moreover, the ratios of N:P:OM in the demand did not match the ratios in the harvested products from NS systems. The matching of these ratios is another topic for future research.

This research concludes that combining UA and NS offers the possibility to increase urban self-sufficiency, and that the city of Rotterdam can fertilize the number of ha of available arable land (2363 ha) and rooftop area (906 ha) with the current population in terms of P and partly in terms of N and OM. However, many uncertainties still remain when determining the extent to which UA and NS can be integrated, including risk analysis for pathogens and micro-pollutants, spatial requirements, effectiveness of recovered fertilizer products in agriculture, and social acceptance.

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