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Assessment of nitrogen and phosphorus flows in agricultural and urban systems in a small island under limited data availability

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ABSTRACT

Nitrogen (N) and phosphorus (P) are two essential macronutrients required in agricultural production. The major share of this production relies on chemical fertilizer that requires energy and relies on limited resources (P). Since these nutrients are lost to the environment, there is a need to shift from this linear urban metabolism to a circular metabolism in which N and P from domestic waste and wastewater are reused in agriculture. A first step to facilitate a transition to more circular urban N and P management is to understand the flows of these resources in a coupled urban-agricultural system. For the first time this paper presents a Substance Flow Analysis (SFA) approach for the assessment of the coupled agricultural and urban systems under limited data availability in a small island. The developed SFA approach is used to identify intervention points that can provide N and P stocks for agricultural production. The island of St. Eustatius, a small island in the Caribbean, was used as a case study. The model developed in this study consists of eight sub-systems: agricultural and natural lands, urban lands, crop production, animal production, market, household consumption, soakage pit and open-dump landfill. A total of 26 flows were identified and quantified for a period of one year (2013). The results showed that the agricultural system is a significant source for N and P loss because of erosion/run-off and leaching. Moreover, urban sanitation systems contribute to deterioration of the island's ecosystem through N and P losses from domestic waste and wastewater by leaching and atmospheric emission. Proposed interventions are the treatment of blackwater and greywater for the recovery of N and P. In conclusion, this study allows for identification of potential N and P losses and proposes mitigation measures to improve nutrient management in a small island context.

1. Introduction

Cities are centres of resource consumption and waste production. Urban systems have been compared to organisms or ecosystems that have a metabolism. Kennedy et al. (2007) defined this urban metabolism as the technical and socio-economic processes that occur in cities, resulting in growth, production of energy and waste. It has been suggested that this metabolism of cities is mainly linear or throughput oriented, but should be changed to a more circular approach in which resources are used efficiently and reused as much as possible (Girardet, 2004; Agudelo-Vera et al., 2012). In particular, the reuse of nutrients such as N and P from urban areas has been suggested as an option that makes it possible to reduce environmental pressures from nutrient losses. Reuse of these nutrients is crucial because the fossil fuel based energy used for production of N-fertilizer via the Haber-Bosch process is approximately 37–45 kJ/gN (Maurer et al., 2003). The global energy requirement for this process is equal to about 1% of the world's total annual energy supply (Smith, 2002). P-fertilizer is obtained from mining phosphate rock, which is a finite and non-renewable resource that is estimated to be depleted in the next 50 to 400 years (Cordell et al., 2009; Sattari et al., 2012; Scholz et al., 2013; Reijnders, 2014).

Cities rely on their hinterlands for food production. The word hinterland is originating from German and literally means the “land behind” and is defined as the region, economically tied to an urban area (Baccini and Brunner, 2012). In the present globalised economy, this urban hinterland is extended to the entire globe. Therefore, it is hard to progress towards a so-called circular or reuse oriented city system where resources, such as the non-renewable P, can be continuously recycled. For example, cities rely on imported food for human consumption, and fertilizers containing N and P for agricultural production (e.g. P is mainly sourced in Morocco and China) (Ma et al., 2010; van Dijk et al., 2016). By recycling these resources locally from domestic waste and wastewater and reusing them in nearby agricultural production, the potential loss of N and P can be reduced and the production and mining of nutrients reduced. Progressing towards this circular system is further

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challenging, because of the large number of agents involved in this system change; these actors include: food supplier, waste producer, and farmers at the local scale (Fernandez-Mena et al., 2016).

The problems that cities face are even more amplified on small islands (Deschenes and Chertow, 2004). They represent physically constrained systems with unique challenges that are characterized by small size, insularity, remoteness, proneness to natural disasters, social isolation, and external dependency (Briguglio, 1995; Méheux et al., 2007; Saint Ville et al., 2015). Because of limited resource availability, most resources in small islands have to be imported for a large part of their domestic needs (Krausmann et al., 2014). Furthermore, the terrestrial ecosystems have a limited buffering capacity as there are few or no surface water systems to attenuate pollution with N and P, before entering the marine ecosystem. In the marine ecosystems, elevated N and P concentrations cause eutrophication. This can lead to decreased water transparency, extinction of fish species, death of coral reefs, change of the zooplankton community and the emergence of toxic phytoplankton species (Pinto-Coelho and Bezerra-Neto, 2005; Howarth and Marino, 2006; Martinelli et al., 2006). In addition, the leaching of nutrients will threaten the quality of the small island's groundwater lenses (Dillon, 1997). This makes small islands highly vulnerable to both global economic change and domestic environmental degradation. Hence, the concept of reusing N and P to protect the marine ecosystem and to achieve self-sufficiency in food production is especially appealing to small islands (Douglas, 2006; Forster et al., 2011).

A key requirement for development and planning of reuse is a good understanding of the resource flows through urban systems and their hinterlands. This requires data about the urban system, its hinterland and its sub-systems (Billen et al., 2012). Billen et al. (2012) investigated the issue of closing nutrient cycles in different cities and indicated the necessity to connect urban and hinterland systems. However, the data for closing the nutrient cycles is often not readily available, in particular when investigating the interlinkages between cities and their hinterland. Montangero et al. (2007) indicated that one of the constraints to the quantification of N and P flows is related to the difficulty of obtaining adequate data. A number of studies, therefore, aim to provide methods to conduct Material or Substance Flow Analysis under uncertain or limited data situation (Huang et al., 2007; Montangero and Belevi, 2008; Do-Thu et al., 2011; Espinosa and Otterpohl, 2014). In these studies, the methodology of Material Flow Analysis (MFA) and Substance Flow Analysis (SFA) has been adapted to assess urban water management in Kun Ming City, China (Huang et al., 2007), to optimise nutrient management in environmental sanitation systems in the urban context of Hanoi City, Vietnam (Montangero and Belevi, 2008), to assess nutrient management in the rural area of Hoang Tay and Nhat Tan communes, Vietnam (Do-Thu et al., 2011), and to assess urban water and wastewater management system in the city of Tepic, Mexico (Espinosa and Otterpohl, 2014). The methodology applied in these studies relies on the maximum use of incomplete local data, and the use of data retrieved from literature or expert judgement. However, the limitation of these studies is that the agricultural system component is not or not well described, because it was not included in the system boundaries or because data was very difficult to obtain.

SFAs have been used to quantify the loss of N and P flows at different spatial scales, but have not been applied to small islands to couple urban-agricultural systems. For example, the flows of N and P related to agricultural systems have been studied at global (Liu et al., 2008; Bouwman et al., 2009), national (Antikainen et al., 2005; Chen et al., 2008; Smit et al., 2010; Ott and Rechberger, 2012; Senthilkumar et al., 2012; Cooper and Carliell-Marquet, 2013; Smit et al., 2015), or city level (Schmid Neset et al., 2008; Li et al., 2011; Wu et al., 2014). Moreover, the SFA and MFA methods have been applied to study N and P flows related to sanitation systems in urban areas of developed countries (Belevi, 2002; Sokka et al., 2004; Meinzinger et al., 2007) and developing countries (Huang et al., 2007; Meinzinger et al., 2009).

The objective of this study is to develop an SFA approach for the assessment of coupled agricultural and urban systems under limited data availability in a small island. The island of St. Eustatius in the Caribbean was used as a case study. The developed approach aims to provide useful information for policy makers to improve nutrient (N and P) management by identifying the source of the nutrient losses and stocks that are potentially available for agricultural production.

2. Methodology

2.1. Description of the study area

St. Eustatius is a small tropical island in the Caribbean and is since 10th October 2010 officially a special municipality of the Netherlands. Formerly, St. Eustatius was part of the Netherland Antilles, which was a constituent country of the kingdom of the Netherlands. The island has a total area of 21 km^2 and a population of 3897 people in 2013 (CBS, 2014). Geologically, the island has mountain-like areas in the south and north (Fig. 1). The south is characterized by the 600 meter-high dormant volcano Quill, and the smaller pair Signal Hill/Little Mountain and Boven Mountain to the northwest. These areas are mostly covered by natural vegetation. Urbanisation on the island is located mostly in the western part of the island. Urban dwellings are scattered in a largely green area in the eastern part (Hoogenboezem-Lanslots et al., 2010).

Agricultural activities on the island consist of livestock and horticulture production. Most animal products from St. Eustatius are consumed locally or exported to the neighbouring islands, while crop products are locally distributed. Since the agricultural sector of St. Eustatius is limited, the food system of St. Eustatius is dominated by import; only 6% of the consumed food is of local origin. However, St Eustatius has potential for development, as historically it has played a prominent role in agricultural production in the region (Ayisi, 1992; Schutjes, 2011). Currently, St. Eustatius has 143.7 ha of agricultural land (6.8% of the total area), consisting of 3.6 ha arable land (horticulture) and 140.1 ha pastures (Smith et al., 2013).

The solid waste generated on the island is collected and dumped in an open landfill. Cistern flush toilets with soakage pits are the most common on-site wastewater systems in St. Eustatius. Most of the pits on the island only receive blackwater, which is the mixture of urine, faeces, and flushing water. The liquid fraction from the pits infiltrates to the groundwater, while the sludge remains in the pit. Greywater, which is generated in the kitchen and from washing activities, such as doing the laundry, dishwashing and other kitchen activities, showering and bathing, is discharged to the open ground.

2.2. Research approach

The method used in this study is Substance Flow Analysis (SFA) (Bringezu et al., 2009). The core principle of SFA is the mass balance principle, derived from the law of mass conservation (Van der Voet, 2002). It is used to determine the magnitude and location of losses and stock changes of substances in the system (Bringezu and Moriguchi, 2002; de Haes and Heijungs, 2009).

The system boundary applied in this study is the geographical land border of St. Eustatius (terrestrial region). Fieldwork was conducted in 2014 to collect background information on domestic waste and wastewater management, agricultural systems, and environmental conditions in the study area. During this fieldwork, it became apparent that the quality and quantity of the data available at St. Eustatius were not suitable to carry out a comprehensive SFA. Table 1 shows all the data that was collected during interviews, retrieved from government reports and from online databases. The 11 interviews that were carried out covered nearly all the officials from the municipality, private companies, and non-governmental organisations (NGOs) on the island. In particular, during the interviews with the three farmers, it became clear

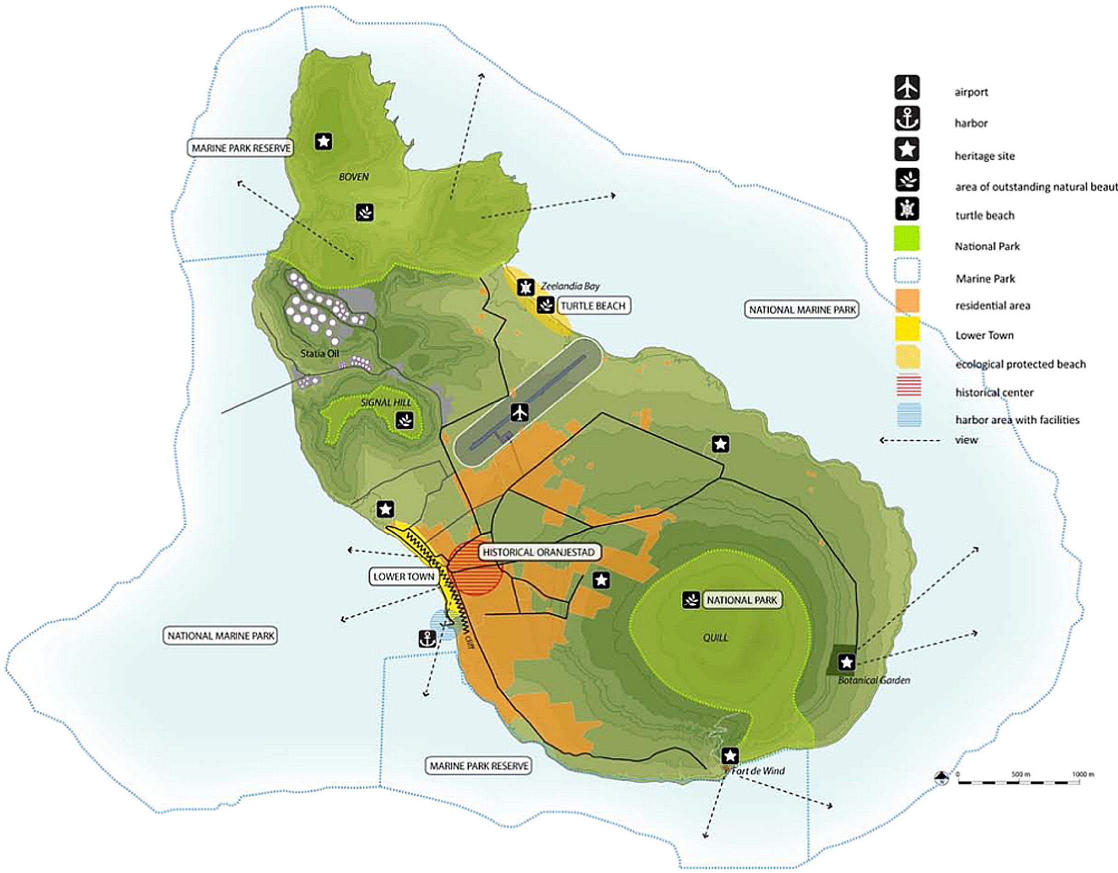

Fig. 1. Map of St. Eustatius (Hoogenboezem-Lanslots et al., 2010).

that the quality of the data was poor, due to the lack of official records, billing or other management information, which are typical for EU farming businesses.

In this study, eight sub-systems were defined with stocks, input and output flows. These sub-systems are agricultural and natural lands, urban lands, crop production, animal production, market, household consumption, soakage pit, and open-dump landfill (Fig. 2). Twenty-six flows associated with the movement of materials containing N and P through the sub-systems and its quantification methods were identified (Fig. 2; detail for calculation in the supplementary material table A1). The year of 2013 was selected as a reference year. The STAN version 2.5 software (Cencic and Rechberger, 2008) was used for consideration of uncertainties, data reconciliation, and visualisation.

2.3. Data sources and quantification per sub-system

2.3.1. Crop production

The sub-system of crop production includes arable land (horticulture) for vegetable products for local food and pastures for local animal feed. The food products represent a flow to the market sub-system, while the feed products are flows to the animal production sub-system. The crop production sub-system receives input flows of N and P from crop uptake (F1). Crop uptake (F1) is defined as the total amount of N and P in products that leave the agricultural and natural lands. Crop residues that remain on the field are regarded as an internal flow and are not studied separately. N and P in vegetable products (F2) are estimated based on the nutrient content of the products. N and P in local animal feed (F3) are estimated from the total nutrient requirement of livestock in St. Eustatius. The nutrient requirements were calculated as the requirements for maintenance and growth. The nutrient requirements for maintenance per beef cattle were based on NRC (2000), and for maintenance per goats and sheep were based on NRC (2007). These nutrient requirements were adjusted using factor 0.6 for beef cattle, 0.8 for goats and 1 for sheep to correct for a lower weight of animals at St. Eustatius (FAO, 2015). The nutrient requirement for growth is assumed equal to the content in slaughtered animals based on the assumption of no changes in the total amount of animals on the island.

2.3.2. Animal production

The sub-system animal production comprises of N and P flows associated with the production of livestock, feed consumption, and the generation of manure. Livestock receives nutrients through feed consumption and most of the nutrients leave the animal body through manure excretion. In St. Eustatius, most livestock is roaming freely on the island, while only a small number of livestock are kept in a stable or a fenced area (Debrot et al., 2015). The roaming animals receive the nutrients from local feed uptake, while the fenced animals receive the nutrients from both local and imported feed. Within this sub-system, N and P flows are explicitly shown in the flows of imported feed (F4), locally produced feed (F3), manure (F9), and livestock for slaughter (F5). According to the mass balance principle, manure (F9) is calculated as the inputs of local and imported feed minus the output of livestock for slaughter. N-gas emission from manure and fertilizer (F24) in this sub-system is calculated based on the assumptions of Sutton et al. (2013). To estimate the nutrient flow of imported feed (F4) and locally produced feed (F3) total nutrient requirement for livestock was calculated. It is assumed that 80% of all livestock consumed local feed because of the high ratio of roaming animals, while the remaining 20% livestock consumed feed with a ratio between local and imported feed of 50:50. Following the standard of Tropical Livestock Units (TLUs) (FAO, 2015), the average weight of cattle is 250 kg, and goats and sheep are 30 kg each. The nutrient content per live weight is assumed for beef cattle (27 g N/kg, 7.4 g P/kg), goat (24 g N/kg, 7.9 g P/kg), and sheep (25 g N/kg, 7.8 g P/kg) (Bruggen, 2007).

Table 1
List of available data collected during fieldwork in 2014 and from secondary data sources.

Description of data and data source	Unit	Value
Population (CBS, 2014)	Inhabitants	3897
Additional number of visitors[a]	Persons	196
Total land (Smith et al., 2013)[b]	ha	2109
Agricultural land		
Arable land (horticulture)	ha	3.6
Pastures	ha	140.1
Natural land		
Rangeland	ha	768
Forest	ha	866
Bare/sparsely vegetated	ha	151
Urban land	ha	181
Livestock (Debrot et al., 2015)		
Beef cattle	cows	1012 ± 468
Goats	goats	2470 ± 807
Sheep	sheep	1300 ± 992
Food consumption in Netherland Antilles (FAOSTAT, 2014)		
Total food protein	g/cap per day	93.2
Total animal protein	g/cap per day	58.4
Total vegetable protein	g/cap per day	34.7
Local vegetable production (Hazel, 2014)		
Tomatoes	kg/year	7650
Cucumber	kg/year	8765
Lettuce	kg/year	3265
Water Melon	kg/year	3360
Spinach	kg/year	406
Pineapple	kg/year	1600
Pumpkins	kg/year	4425
Exported animal products (LVV, 2014)		
Cows meat (carcass)	kg/year	18,583
Goat meat (carcass)	kg/year	328
Sheep meat (carcass)	kg/year	1126
Imported fertilizer (Hazel, 2014)		
NPK fertilizer (13-13-13)	ton/year	1
Municipal waste production (DEI, 2014)		
Household organic waste (kitchen waste)	kg/cap per year	39.3
Market waste (restaurants, supermarkets)	kg/cap per year	35.4

[a] The number of visitors was estimated based on 10,250 tourists visiting the island per year (Tieskens et al., 2014) and an assumed average stay of 7 days.
[b] Analysis of satellite images results in unclassified areas because of cloud cover (219 ha). The area was allocated for 1/3 to natural land–rangeland, 1/3 to natural land–forest and 1/3 to urban and industrial land, based on the map of St. Eustatius.

2.3.3. Market

All products needed for domestic consumption are distributed to the household through the market sub-system, while some animal products are exported outside the system. The flows containing N and P include the processing and trade of local and imported food, imported detergent and the use of the detergent by households. The market sub-system consists of the flows of vegetable products (F2), livestock for slaughter (F5), exported animal products (F6), slaughtered animal waste (F7), imported food (F12), imported detergent (F14), food (F10), detergent use (F13) and market waste from supermarkets and restaurants (F11). The N and P content in the vegetable products transferred to market sub-system was estimated based on The Souchi Fachman Kraut (SFK) online database (Souchi, 2001). SFK online database provides the composition of various food items with different constituents including detailed information on nutrition contents.

The imported food flow represents food products of both plant and animal origin that are transported to St. Eustatius. Due to lack of detailed information on the types of imported products, the N and P contained in the imported food (F12) are estimated based on the difference between the total supply of local food products (animal and crop products) and the sum of food consumed by local people and market waste (see Section 2.3.4). Livestock (F5) is estimated based on the annual number of animals slaughtered for local consumption and export activities. Landbouw, Veeteelt en Visserij (LVV), a local governmental agency focusing on the development of agriculture and fisheries, provided data on the number of animals locally slaughtered, and the amount of exported products in carcass weight (LVV, 2014). About 4 beef cattle, 20 goats and 10 sheep are slaughtered monthly for local consumption. N and P in slaughtered animal waste (F7) are calculated based on the difference between the nutrient content of live animals and animal products. The animal products consist of locally consumed (only meat fraction) and exported products (meat with bones). The fraction from live animal to carcass and carcass to meat was derived from Smit et al. (2015).

2.3.4. Household consumption

The N and P flows to the household consumption sub-system are calculated based on the total food consumed by local people and tourists. It is assumed that tourists' food consumption is similar to local food consumption. This consumption takes place in households, restaurants, and offices. Food consumed by households is partly excreted as blackwater (faeces and urine) and partly disposed of as kitchen waste. The N and P contained in the food flow (F10) are calculated based on FAO country specific food supply information. The average total food protein supply of the Netherland Antilles is 93.2 g/cap per day in 2010 (FAOSTAT, 2014). The N and P contained in food supply are calculated based on the formula determined by Vinnerås and Jönsson (2002) using the FAO country specific food supply information and the fact that plant food protein contains on average twice as much P per gram as compared to animal protein (Vinnerås and Jönsson, 2002; Jönsson et al., 2004).

The use of detergent (F13) for laundry and dishwashing contributes to the P losses through the discharge of greywater (F15). These flows represent the amount of imported detergent to St. Eustatius (F14). It is assumed that the detergents do not contain N. P emission of laundry detergent and dishwasher detergent is estimated using information of Van Drecht et al. (2009) (see supplementary material table A1), amounting to 0.62 kg P/cap per year.

2.3.5. Soakage pit

The soakage pits described in this study only receive blackwater (faeces, urine, and flush water). The toilets in St. Eustatius are generally constructed with a single pit, where the liquid fraction of the blackwater infiltrates into the ground through the bottom, and the solids accumulate in the pit as faecal sludge. Transfer coefficients for N to faecal sludge in pit latrines are estimated to range from 9 to 27%, with the remaining N going to leachate (Montangero and Belevi, 2007). Similarly, of the total P input flow to the soakage pit (F17), 18–40% remains in faecal sludge, and the remaining 60–82% is leached (Montangero and Belevi, 2007). Another study indicated that 2–20% of total N and <1% of total P are lost to groundwater from pit latrines (Nyenje et al., 2013). This low percentage of leaching is due to the type of soil and the type of ventilated pit latrine system applied, where some of the N is emitted to the atmosphere. Within the present study, nitrogenous gas emission from the soakage pit (F19) is not considered because the pit is located underground, preventing ammonia emission. Moreover, nitrification will be limited as mainly anaerobic conditions prevail in the pit. In St. Eustatius, soils are generally well draining. Therefore, the amount of N and P transferred to urban land is estimated based on the transfer coefficients for leachate from Montangero and Belevi (2007). As there is an accumulation of N and P in the pit, a stock change (P1) is taken into account in the sub-system.

2.3.6. Open-dump landfill

Within this study, the flows of slaughtered animal waste (F7), kitchen waste (F16) and market waste (F11) are considered as input flows to the open-dump landfill sub-system. Output flows include leachate (F20) and nitrogenous gas emission (F21). A stock (P2) is included in this sub-system to represent the amount of N and P accumulating in the landfill. To estimate N and P content in input flows of supermarket waste (F11) and kitchen waste (F16), a percentage of dry matter of

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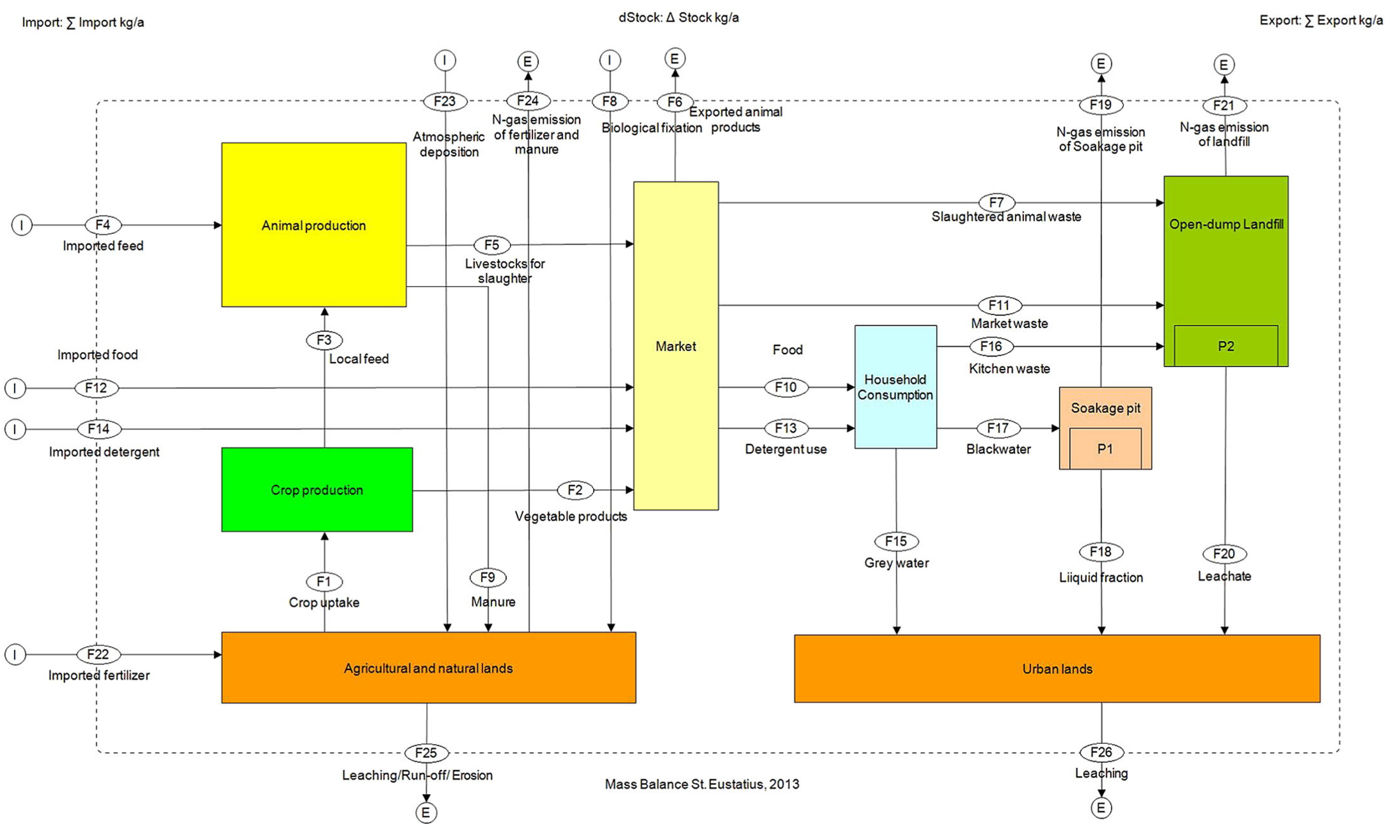

Fig. 2. Schematic representation of analysed system using STAN 2.5 (Cencic and Rechberger, 2008); baseline study in St. Eustatius.

40% is assumed (Eggleston et al., 2006), and N and P concentrations in the dry matter of 3.16% and 0.52% respectively (Zhang et al., 2007).

The quantity of N lost from waste is associated with the volume of water that percolates through the landfill. N is lost from the open-dump landfill sub-system through leachate and nitrogenous gas emission. Landfill leachate is mainly generated due to rain water percolating through the waste (Mahmud et al., 2012). Factors affecting the amount of N that is leached are related to the age of landfill, the climate that influences precipitation and evaporation, seasonal weather variation, waste type and composition, water content and the degree of compaction of the waste (Renou et al., 2008). Due to lack of data on the leachate concentration and volume of gas generation from landfill in St. Eustatius, transfer coefficient of total N from landfill to leaching is estimated to range from 21 to 27% (Wang et al., 2014), and to gas emission from 16 to 25% (Onay and Pohland, 1998). Because P movement is not linked to water percolation, but rather to movement of sediments, leaching is not taken into account for P (Kjeldsen et al., 2002). Erosion is not taken into account as the waste fraction remains on the open-dump landfill sub-system. As there is no P emission to the atmosphere, 100% of P accumulates in the landfill.

2.3.7. Agricultural and natural lands

The agricultural and natural land sub-system is a nexus for many N and P flows. Some of the flows are already described in previous sections except for imported fertilizer (F22), atmospheric deposition (F23), biological nitrogen fixation (F8), nitrogenous gas emission from fertilizer and manure (F24) and leaching/erosion/run-off (F25). Within this sub-system, it is assumed that P can accumulate in the soil, while there is no N accumulation in the soil (Sutton, 2013). The absence of N accumulation in the agricultural and natural land sub-system is based on a steady state approach by assuming no change in soil organic matter content (Van Drecht et al., 2003).

There are no official records of chemical fertilizer use in St. Eustatius. Therefore, data on the amount of imported fertilizer is retrieved from a local farmer (Hazel, 2014). The application rate of fertilizer is assumed to be the same for the other farmers and applied on the total arable land. Based on Cleveland (1999), the amount of symbiotic and non-symbiotic biological N fixation is estimated as 2.7 kg N/ha for grassland and an average of 23 kg N/ha for forest and shrub land (Cleveland et al., 1999). For terrestrial regions in remote areas, N deposition is estimated about 0.5–1 kg N/ha per year (Galloway et al., 2004). Annual P deposition on the island of St. Eustatius is estimated to be 0.05 kg P/ha, based on simulation of long-range atmospheric P transport by Mahowald et al. (2008), cited by (Tipping et al., 2014).

In the agricultural and natural sub-system, total N loss was calculated based on the N surplus. N is lost from the agricultural and natural sub-system through ammonia volatilization, soil denitrification, and leaching and runoff (Cameron et al., 2013). For the present study, global estimates reported by Sutton et al. (2013) were used to estimate the division of N loss over these routes: 24% is lost as ammonia, 16% by soil denitrification and 60% by leaching and runoff. P losses through erosion and runoff were estimated based on measured export of P from Caribbean tropical rainforest catchments in Dominica, St Lucia, and St. Vincent (McDowell et al., 1995). Export of P from different catchments varied between 0.03 and 0.48 kg P/ha per year, with an average of 0.134 kg P/ha per year. Average annual rainfall on the three islands is 2083, 2301 and 1583 mm/year respectively (FAO, 2016), which is about twice the amount of rainfall on St. Eustatius in 2013 (SEAWF, 2016). Based on these differences in rainfall, export of P by erosion and runoff from St. Eustatius was estimated at half the average amount measured by McDowell et al. (1995).

2.3.8. Urban land

Urban land sub-system includes the land or soil that receives N and P discharged from the household sub-system in the form of greywater (F15), leachate from the open-dump landfill sub-system (F20) and the liquid fraction from the soakage pit sub-system (F18). N leaches and

Table 2
Uncertainty level with corresponding uncertainty factors and coefficient variance (CV) applied for different data sources.

Level	Uncertainty factor	Coefficient variance (CV)	Information source	Example
1	1.11	±10%	Official national/local statistics, published paper/report related to St. Eustatius or in the region of Caribbean	Food consumption data
2	1.33	±25%	Unpublished reports, published paper/report from global study	Animal production data
3	2	±50%	Experts estimation	Imported fertilizer, agricultural production

infiltrates into ground water (F26) and leaves the system boundary, while P accumulates in the soil as net stock.

2.4. Uncertainty analysis

The methods applied to quantify N and P flows in this study are various and characterized by different levels of uncertainty. The uncertainty analysis applied in this study using the concept introduced by Hedbrant and Sörme (2001), to estimate uncertainties of N and P flows. The concept is based on the categorisation of data sources. The data sources were categorised based on the availability of the data ranging from national to local data, published or unpublished data, and these data were ranked based on the estimated reliability. Each data set was assigned an uncertainty level corresponding to an interval established by an uncertainty factor, corresponding to the representativeness and accuracy of the data source and resulting in an estimated uncertainty range. Since the method of Hedbrant and Sorme (2001) produced asymmetrical intervals as uncertainty, the method of Laner et al. (2015) was applied to modify the asymmetrical interval into symmetric interval for use with the STAN software. In this adaptation, the uncertainty factors are converted into coefficients of variation (CV) (See Table 2). Laner et al. (2015) define the CV as the mean value plus two standard deviations, with a symmetric interval around the mean corresponding to a 95% confidence interval.

Level 3 was assigned to the data retrieved through interviews, such as data of imported fertilizer and agricultural production, as these interviews generally yielded data from memory. Level 2 was assigned to the data retrieved from unpublished reports provided by local authorities, such as animal production data. This data range was chosen as these reports have not been approved or validated. The least uncertain information sources are official statistics and published papers or reports. Level 1 was assigned to these data sources. For the generally accepted knowledge (e.g. molar mass), there is no uncertainty level assigned to this type of data.

The software STAN was used for modelling substance flows and for data reconciliation including the uncertainty analysis (Cencic and Rechberger, 2008). In STAN, all uncertain data and parameters are described by normally distributed independent random variables. Uncertain quantities are expressed by the mean and a measure of variance based on the standard deviation. Furthermore, STAN use Gaussian error propagation and data reconciliation to calculate the uncertainty of model outputs if there is a conflicting uncertain data (Laner et al., 2014). The analysis in STAN will balance the results based on the uncertainty associated with each flow (see supplementary material table A2).

3. Results

3.1. Overall balance

St. Eustatius receives a total input flow of 65,304 ± 8% kg N/year and 3861 ± 11% kg P/year, with a total output flow of 59,890 ± 10% kg N/year and 356 ± 20% kg P/year (Figs. 3 and 4). Therefore, a net stock change of 5414 ± 67% for N and 3505 ± 12% for P takes place annually. The natural input flows to the system are associated with the N-

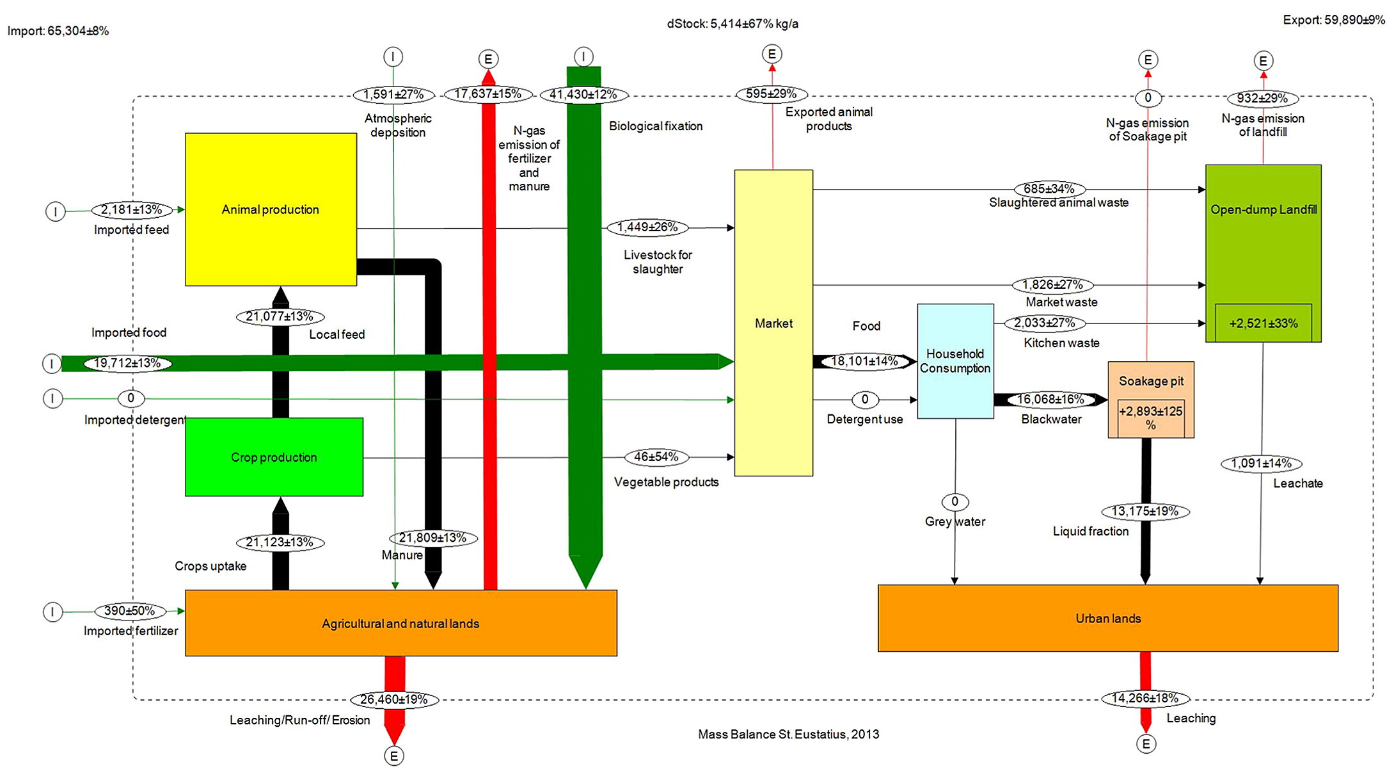

Fig. 3. The flows and stock change of N in St. Eustatius (kg N/year).

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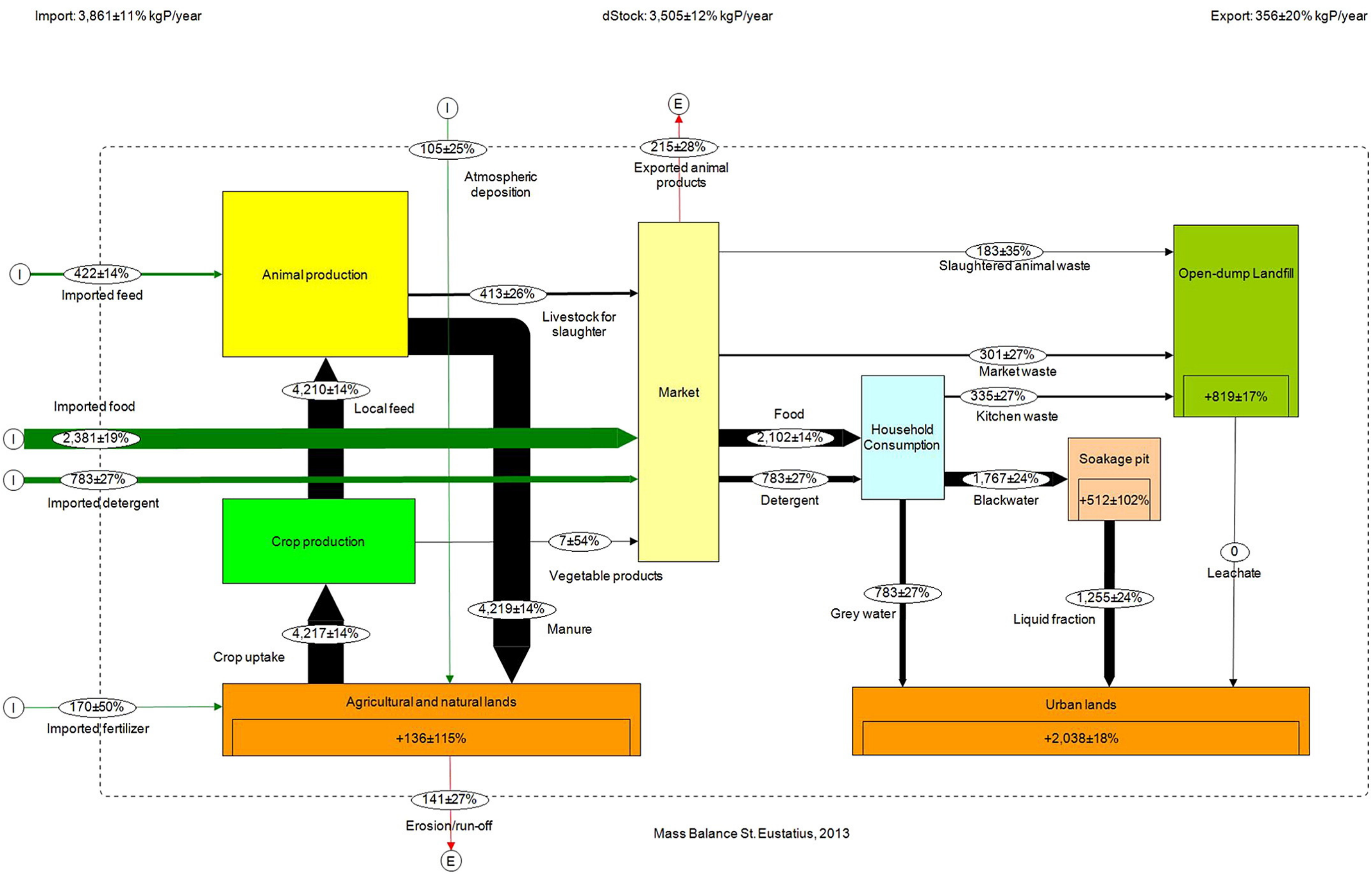

Fig. 4. The flows and stock change of P in St. Eustatius (kg P/year).

biological fixation (41,430 ± 12% kg N/year) and atmospheric deposition (1591 ± 27% kg N/year and 105 ± 25% kg P/year). The main anthropogenic N and P inputs to the system are via imported food: 30% of the total N inflow (19,712 ± 13% kg N/year) and 61% of total P inflow (2381 ± 19% kg P/year). Imported feed, fertilizer, and detergent containing N and P represent about 4% of N and 36% of P of the total input flows.

The amount of N that is lost from the system comprises of leaching/run-off of agricultural and natural lands (44% of N; 26,460 ± 24% kg N/year), leaching from urban lands (24% of N; 14,266 ± 18% kg N/year), N-gas emission from fertilizer and manure (29% of N; 17,637 ± 15% kg N/year), exported animal products (1% of N; 595 ± 29% kg N/year), and N-gas emission from landfill (2% of N; 932 ± 29% kg N/year). P leaves the island mainly through exported animal products (6% of imported P; 215 ± 28% kg P/year); the P loss from erosion/runoff from agricultural and natural lands is relatively small (141 kg P/year) as the P content of the eroded soil is low. Most P accumulates in the land systems soakage pit and landfill. This P is currently inaccessible for reuse in agriculture.

3.2. Balance per sub-system

The total crop uptake in the crop production sub-system is 21,123 ± 13% kg N/year and 4217 ± 14% kg P/year. Of this total flow, local animal feed contains 21,077 ± 13% kg N/year and 4210 ± 14% kg P/year that are transferred to the animal production sub-system, and local vegetables contain 46 ± 54% kg N/year and 7 ± 54% kg P/year that are transferred to the market sub-system. Similar to local vegetables, livestock for slaughter (1449 ± 26% kg N/year and 413 ± 26% kg P/year) are transferred from the animal production sub-system to the market sub-system. These local animal and vegetable products represent 8% of N and 19% of P consumed by local people and tourists in the household consumption sub-system, in which total food consumption is accounted for 18,101 ± 14% kg N/year and 2102 ± 14% kg P/year.

The N and P entering the household consumption sub-system are transferred to blackwater (16,068 ± 16% kg N/year and 1767 ± 24% kg P/year), greywater (783 ± 27% kg P/year), and are disposed of as kitchen waste (2033 ± 27% kg N/year and 335 ± 27% kg P/year) to the landfill. All of the calculated P content in greywater originates from the detergent. About 11% of N and 16% of P in total food consumption by households is disposed of as kitchen waste. Blackwater contains 77% of N and 72% of the P consumed. Of the total N and P in blackwater, 80% of N (13,175 ± 19% kg N/year) and 71% of P (1255 ± 24% kg P/year) are leaching from the soakage pit and enter the soil system. N is then washed out to the ground water, while the PO_4^{3-} ions are partly adsorbed to soil minerals, and partly leached due to high water use for flushing toilets (about 10 l per flush) in St. Eustatius. The remaining 20% of N (2893 ± 125% kg N/year) and 29% of P (512 ± 102% kg P/year) are retained in the soakage pit as sludge.

The main N and P input to the open-dump landfill sub-system are kitchen waste (2033 ± 27% kg N/year and 335 ± 27% kg P/year), market waste (1826 ± 27% kg N/year and 301 ± 27% kg P/year), and slaughtered animal waste (685 ± 34% kg N/year and 183 ± 35% kg P/year). Of the total input to the landfill, about 21% of N (932 ± 29% kg N/year) is lost to the atmosphere, nearly 24% of N (1091 ± 14% kg N/year) leaches, and nearly 55% of N (2893 ± 125% kg N/year) accumulates in the landfill. In following years, the organic matter containing this N might be degraded, releasing N to the atmosphere or ground water. All P entering the open-dump landfill accumulates (819 ± 17% kg P/year). Some P remains in the landfill in the pile of waste, like part of the P in slaughter waste such as bones, which is not susceptible to leaching. Another fraction of waste in the landfill is easily degradable, and the nutrients can leach into the soil under the landfill, where it is assumed to be retained as a result of the P sorption capacity of the soil (Sharma et al., 2015).

Most N and P from the animal production sub-system are transferred to the agricultural and natural lands sub-system as manure (21,809 ± 13% kg N/year and 4219 ± 14% kg P/year). N and P uptake by local crops (21,123 ± 25% kg N/year and 4217 ± 14% kg P/year) are a bit smaller than the input with manure. The agricultural and natural land sub-system has a net P stock change of 136 ± 115% kg P/year. N loss from the agricultural and natural land sub-system is through N-gas emission, leaching, and erosion/run-off. About 40% of N loss is emitted to the atmosphere due to ammonia volatilization, N_2 and N_2O emission, which accounted for 17,637 ± 15% kg N/year. Additionally, about 60% of N is lost through leaching and erosion/run-off, which accounted for 26,460 ± 19%. In the urban land sub-system, P accumulation accounts for 2038 ± 18% kg P/year. For the case of N, a total of 14,266 ± 18% kg N/year leaches from urban land sub-system.

4. Discussion

4.1. Comparison with other SFA studies

Comparison of the results with other SFA studies shows that the results for St. Eustatius are not well comparable (Table 3). Only for the Net stock for P are the values comparable. These differences indicate the specific characteristics of small islands such as St. Eustatius. The very low agricultural input and the very low imported mineral fertilizer (N&P) provide evidence for the subsistence agriculture on the island. Even compared to cities such as Bangkok, which have a relatively high population compared to agricultural production and thus low per capita imports, the levels for St. Eustatius are low. This is not surprising as there are only about 3.6 ha of land currently farmed using mineral fertilizer. Table 3 also shows that there is no recovery of N and P from wastewater, which is another specific characteristic of St. Eustatius. However, at the same time, the evidence shows that the stock increase for P is comparable to other cases studies, while the N stock increase even exceeds those of the two other studies available (only two studies). The reasons for this are related to high biological nitrogen fixation (BNF) on the island, in which high amounts of N are fixed by invasive species such as *Caesalpinia bonduc* and *Tamarind* (Smith et al., 2013). Other reasons are also related to the high meat diet and a direct discharge of the wastewater to the soil matrix (for P) that contributes to a high stock increase. In addition, this study includes a more detailed assessment of the "natural" N-cycle, to which other studies have not paid as much attention. In conclusions, the comparison shows that the variation between the present and other studies is large. However, a closer look at the data also shows that the variation between the other studies is large (Table 3 - e.g. Ma et al. (2010) for imported mineral fertilizer >40 times this of Færge et al. (2001) and Meinzinger et al. (2009); Net stock for P Ma et al. (2010) almost 8 times higher than Færge et al. (2001)). This suggests that these substance flows are reflections of the socio-economic as well as natural conditions of each case (Fernandez-Mena et al., 2016; Voskamp et al., 2016).

4.2. Identification of intervention points

The results show that 57% of the N and 1% of the P are lost from the agricultural and natural land in St. Eustatius through leaching, nitrogenous gas emission, and erosion/run-off. Most of the P accumulates in the urban land. The annual stock change for N in soakage pits, landfill, and urban land is about 5400 kg or 14 times the annual fertilizer import or 2 times the combined feed and fertilizer import. For P, these numbers are even higher accounting for 20 times the fertilizer import and over 6 times the combined feed and fertilizer import. These numbers provide evidence that if only a small fraction of the nutrient flows on the island can be recovered and used, it would be sufficient to sustain the subsistence agriculture. At higher recovery rates, local food and feed production can be increased without increasing the dependency on fertilizer imports.

The system component that is the most likely place for recovery of these nutrients is the urban sanitation system, which consists of the soakage pits and the landfill sub-systems. Accumulation of N mainly takes place in the sanitation system, while P accumulation in the sanitation system contributes 37% to the total accumulation. About 58% of the remaining P accumulates in the urban land, and small percentage (5%) accumulates in the agricultural and natural land. The P that accumulates in the urban soils might not be available to plants as the P is adsorbed below the root zone and cannot be released from the clay minerals. Contrary to this, P that accumulates in the sanitation system and especially in the soakage pits, is easily extractable in a concentrated form as pit sludge (de Graaff et al., 2011).

A further analysis of the key flows in the model enables the identification of other sub-systems for interventions that can improve nutrient management and reduce the environmental impact, such as eutrophication of the marine ecosystem, Green House Gas (GHG) emission and ground water pollution (Smith et al., 1999; Conley et al., 2009). However, while the soakage pit sludge can become a source of N and P, the major fraction of N and P is lost from this sub-system as liquids that enter the soil matrix. This does suggest that the current sanitation system needs modifications to enable maximal nutrient recovery.

The model also showed that animal and crop production sub-systems have large internal flows of N and especially P. These internal flows indicate that the nutrient cycle between crop uptake, feed and manure is largely closed. Most manure is from free roaming animals and this manure is assumed to be deposited where the animals graze. Some N losses take place, but these are compensated by biological fixation by plants. For P, feed consumption and manure excretion largely close the cycle.

Table 3
A comparison of results of this study with the results of other SFA studies for selected indicators: Net stocks (kg N/cap and kg P/cap) indicate accumulations within the analysed system including agricultural and natural soils, and urban soils; Agricultural input from mineral fertilizers (%) indicator measures how reliant the agricultural system is on mineral fertilizers; Imported mineral fertilizers (kg N/cap and kg P/cap) indicator measures the amount of imported mineral fertilizers; N and P recovery from wastewater (%) indicator reveals how much of the N and P from domestic waste and wastewater has been recovered and reused in agriculture as sludge, compost or other recovered products.

				Net stocks		Agricultural input from mineral fertilizers (%)		Imported mineral fertilizer		N and P recovery from wastewater	
SFA study	Scale	Location	Year	N (kg N/cap)	P (kg P/cap)	% N	% P	kg N/cap	kg P/cap	% N	% P
Ma et al. (2010)	Country	China	2005	0.46	2.62	61	69	20.70	3.80	–	–
Antikainen et al. (2005)	Country	Finland	1995–1999	–	–	65	61	–	–	–	24.00
Meinzinger et al. (2009)	City	Arba-Minch, Ethiopia	2009	–	–	67	–	0.50	0.18	–	–
Færge et al. (2001)	City	Bangkok, Thailand	1996	0.15	0.33	7	15	0.37	0.10	7.00	10.00
Aramaki and Thuy (2010)	City	Haiphong, Vietnam	2010	–	–	62	61	1.57	0.80	–	–
Smit et al. (2010)	Country	Netherlands	2005	–	3.80	–	24	–	–	–	6.00
Cooper and Carliell-Marquet (2013)	Country	UK	2009	–	1.90	–	27	–	1.02	–	41.00
This study	Island	St. Eustatius	2013	1.44	0.89	0.04	1.00	0.10	0.04	0	0

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Figs. 3 and 4 indicate that a large amount of N and P accumulates in the open-dump landfill sub-system. The open dump comprises a mixture of waste flows, which makes recovery of nutrients difficult. For nutrient recovery, important resource flows should be separated before they are mixed with other flows. Separating important resource flows at source may result in homogenous waste streams that can be more easily processed and reused. For example, slaughtered animal waste is such a homogenous stream. If slaughtered animal waste is diverted away from the landfill, specific treatment can be applied to enable safe recovery of N and P (Mata-Alvarez et al., 2000; Jensen et al., 2014).

4.3. Improved sanitation - interventions for improving nutrient management

As indicated above, the sanitation system was proposed as one of the most likely places for intervention to improve nutrient management on the island. Potential systems vary from low to highly advance and from centralized to a decentralized system, with multiple technological options all over the process train of collection, transport, treatment/recovery and reuse/disposal (Zeeman et al., 2008; Massoud et al., 2009; Tilley et al., 2014). For a small island like St. Eustatius, a viable treatment system that is low in the capital and operating cost, compatible with the local expertise and institutional framework should be adopted.

Since the location of St. Eustatius is in the tropical region, anaerobic treatment, such as Septic Tank (ST), Upflow Anaerobic Sludge Bed (UASB), UASB-Septic Tank (UASB-ST) (Lettinga et al., 1993; Kujawa-Roeleveld et al., 2005; Zeeman et al., 2008), or Anaerobic Baffled Reactor (ABR) (Hahn and Figueroa, 2015), is a feasible option to improve existing sanitation treatment. The main treatment can be either applied house-on-site or community-on-site. As most households have a soakage pit, treating blackwater in a house-on-site UASB-ST or ST is relatively easy to install and will reduce emission to the soil and groundwater as these systems are closed. A UASB-ST is an improved conventional septic tank producing sludge, biogas, and a liquid effluent containing the majority of the nutrients. Liquid streams from the UASB-ST or ST could be transported to a community-on-site post-treatment for disinfection prior to reuse via a small bore sewer system (Mara et al., 2007), while the producing solid streams (sludge) can be collected by truck, post-composted with kitchen waste and used in agriculture as an organic fertilizer. Such measures will substantially reduce emissions and limit accumulation stocks. Alternatively, the blackwater can be transported via a conventional sewer system to a community-on-site UASB or ABR system. Such community-on-site anaerobic treatment system might enlarge the possibilities for biogas use and therefore the reduction of GHG emissions. However, a drawback of the necessary conventional sewer system is the high costs (Mara et al., 2007).

Additional intervention could be the recovery of struvite from the liquid rich-nutrient effluent of UASB or UASB-ST at community-on-site (de Graaff et al., 2011). Struvite ($MgNH_4PO_4$-$6H_2O$) is a product that can be recovered from concentrated domestic wastewater streams using precipitation technology with the addition of Magnesium (Mg) to recover P (Le Corre et al., 2009; Etter et al., 2011). It can be applied as a good hygienically safe slow release fertilizer (Le Corre et al., 2009; Cordell et al., 2011; Rahman et al., 2014). In the context of St. Eustatius, the liquid effluent of the community- or house-on-site anaerobic treatment system can, instead of direct use (after disinfection) in agriculture also be utilized for struvite recovery. However, this type of intervention is complex and expensive under the conditions prevailing at St. Eustatius, as the existing toilet needs to be adjusted to provide a more concentrated blackwater, and chemicals, such as $MgCl_2$, MgO, or $Mg(OH)_2$, are needed for struvite precipitation (Rahman et al., 2014).

Another possibility is the treatment and recovery of greywater with its included nutrients. The greywater of St. Eustatius is a substantial source of P (10% of total input P). Greywater has a potential as irrigation/fertilisation water, and this resource could be exploited when diverting greywater to agriculture (Al-Hamaiedeh and Bino, 2010). However, using greywater as irrigation water for agriculture might be a challenge due to the spatial separation of agriculture and housing, but it may be feasible by promoting home gardening for the production of fruits and vegetables. The quantification model also reveals that the P in greywater originates from P in detergents. This implies that possible changes in policy or phasing out of P-containing detergents may result in less environmental pressure, but also make this P from detergents a risky resource to rely on in future.

4.4. Impact of interventions towards nutrient recovery

Several sanitation concepts or interventions that can be applied in the context of St. Eustatius will have an impact on the nutrient recovery and reuse. Figs. 2 and 3 illustrate that the N and P containing sludge, retained in the soakage pit, can replace the currently imported fertilizer used in agriculture. About 3758 kg N/year and 439 kg P/year are available in the soakage pit that can be reused in agriculture. However, direct reuse of pit sludge in agriculture is not recommended as it still has high pathogens and micro-pollutants content.

Another concept is the application of UASB-ST to replace the soakage pits. If UASB-ST treats a more concentrated blackwater streams, approximately 80% of N and 40% of P will end in the liquid effluent, while the remainder of the N and the remainder of P will end in the sludge (Kujawa-Roeleveld et al., 2005). Implementation of this concept in St. Eustatius will result in 14,000 kg N/year and 760 kg P/year remaining in the effluent, while almost 2000 kg N/year and 1400 kg P/year remaining in the sludge. As a next step, the sludge of UASB-ST can be co-composted with organic waste streams (e.g. garden waste) to increase the organic matter content of the product in the form of compost for reuse.

Implementation of source-separation concept at household level will also have an impact on the nutrient recovery and reuse. If kitchen waste is separately collected from household, about 4800 kg N/year and 800 kg P/year can be treated together with wastewater (sludge) as proposed by (Larsen et al., 2009; Zeeman, 2012). Thereby, the collection and treatment of kitchen waste will reduce the amount of waste transferred to the open-dump landfill, reduce the N leachate from the landfill, and potentially improve groundwater quality. Moreover, separating urine from blackwater streams at the household level, collecting and treating it for reuse in agriculture will potentially recover 72% of N contained in urine (Larsen et al., 2009). This concept will result in higher nutrient recovery, improving wastewater effluent quality due to lower nutrient concentration in wastewater (Maurer et al., 2003). However, the collected urine needs to be stored at least six months for disinfection to increase the safety use of the urine (WHO, 2006).

The impact on the urban-agricultural system of any technological intervention can be assessed just as it was done for the present sanitation system in St Eustatius. In this way, the largely literature-based model developed in this study allows researchers and planners to first identify the point source of nutrient losses and secondly evaluate the potential interventions for better nutrient management. However, potential interventions for resource recovery also need to be assessed in the context of uncertainties about future developments, such as climate change, societal change, and economic change. These developments may influence both the nutrient balance and the potential applicability and effectiveness of the interventions. Scenarios have been widely applied to deal with uncertainty of future circumstances (Börjeson et al., 2006), for example by building normative scenarios (van der Voorn et al., 2012), or through trend analysis and building explorative scenarios (Van Vuuren et al., 2010; Gerland et al., 2014). Future research should aim to assess the performance of different sanitation technologies under different future development scenarios, by analysing global and regional trends and designing external scenarios.

5. Conclusion

The SFA approach developed in this study is considered as a first step to analyse the actual problems related to nutrient management. As a next step, it allows for the identification of critical intervention points and mitigation strategies for reducing N and P nutrient taking urban-rural development policies on the island into account. Moreover, the results indicate that most N and P loss in St. Eustatius is through erosion/run-off, leaching and gas emission. Accumulation of N and P takes place in the soakage pit and open-dump landfill. These stocks are currently lost and not reused in agricultural. Applying a specific intervention to replace the current sanitation system will have a systemic impact on the overall nutrient balance of St. Eustatius. Planners can, therefore, use this model to make decisions about future interventions for a transition to closing nutrient cycles.

Although the developed model provides N and P balances for the case of St. Eustatius, the approach presented can be applied in other small island systems that face limited data situation. Indeed, most of the resources and methods used in this study do provide important elements that can be adopted for integrated assessment of cities and hinterlands.

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Appendix A. Supplementary materials

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.08.159.

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