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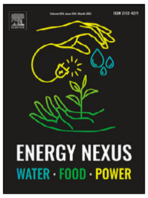

Quantification of the local water energy nutrient food nexus for three urban farms in Amsterdam & Boston

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ABSTRACT

Water, energy and nutrients are interlinked extensively with food and each other as shown in the monitoring, analysis and evaluation framework for the Water Energy Nutrient Food (WENF) nexus by Haitsma Mulier et al. (2022). This study aims to contribute to the quantification of the Water Energy Nutrient Food nexus regarding urban agriculture. It investigates the water, energy and nutrient demand of urban farms along with the presence of those resources in urban waters at three case study sites. Demands for water and nutrients (nitrogen & phosphorus) at a greenhouse in Amsterdam and a community farm and a container farm in East-Boston could be met by resources present in urban waters (rainwater and wastewater) in the direct vicinity. Whether enough energy is available to operate each of these farms is related to the type of agriculture.

Introduction

Consistent with the growing demand for locally produced food, urban agriculture and local decentralized food systems are becoming a worldwide movement. Farming initiatives in cities are responding integrally and adequately to some of the largest challenges the world presently faces, such as population growth, urbanisation, climate change, environmental pollution and resource depletion [12,15,17].Agriculture lies at the core of the (urban) Water Energy Food (WEF) nexus; therefore, it is not surprising that urban agriculture is able to partially address multiple grand challenges for sustainability at once. The WEF nexus, however, misses an essential element for producing food; all agricultural production requires nutrients in addition to water and energy. Therefore, the WENF-nexus is introduced [14], as illustrated in Fig. 1.

Though this article will focus on the role of water in providing nutrients and energy for urban agriculture we have to recognize that, due to a limited availability of space in cities, urban farms are generally operating at a smaller spatial scale than conventional rural farms. Innovative solutions are often applied at commercial urban farms to overcome this constraint. Expanding cultivation surface vertically or growing crops indoors where climate and (artificial) light conditions can be controlled are not uncommon. To prevent soil-borne diseases as a result of the absence of annual freezing and thawing cycles in climate-controlled surroundings, ingenious new soil free culture methods have been developed, such as hydroponics, aeroponics and aquaponics [17,26].

Water, nutrients, solar and thermal energy are all abundant in urban environments in tropical and temperate climate zones, which provides a great opportunity for sustainable reuse of materials from waste streams and for the realisation of circular agriculture in cities; waste management and farming could mutually reinforce each other. Nowadays cities are primarily open loop systems with one-way flows of resources [25]. Using urban by-products of this linear system, such as sewage or solid organic waste like food waste, as inputs in farms blurs the line between wastes and resources. Thus, urban agriculture can reduce the amount of waste output of a city as well as conserve raw natural resources by reducing their input.

The feasibility of creating a closed loop resource system in urban agriculture requires an understanding of the stocks, flows and accessibility of these resources for urban farming projects. However, the mere absence of data collected at a local level impedes informed decision making on nexus sector integration and feasibility of circular solutions. Estimates on resource consumption at farms are often generated using theoretical transpiration models [4,21]. Testing resource requirements in the field, however, is more reliable, since in reality farms are rarely operated at a 100% efficiency level.

In order to study the actual on-site resource flows at urban agricultural initiatives, a monitoring, analysis and evaluation framework for the Water Energy Nutrient Food nexus was created [14] and used to investigate the resource demands of three urban farms and to quantify the available water, energy and nutrients in urban waters surrounding these case study farms.

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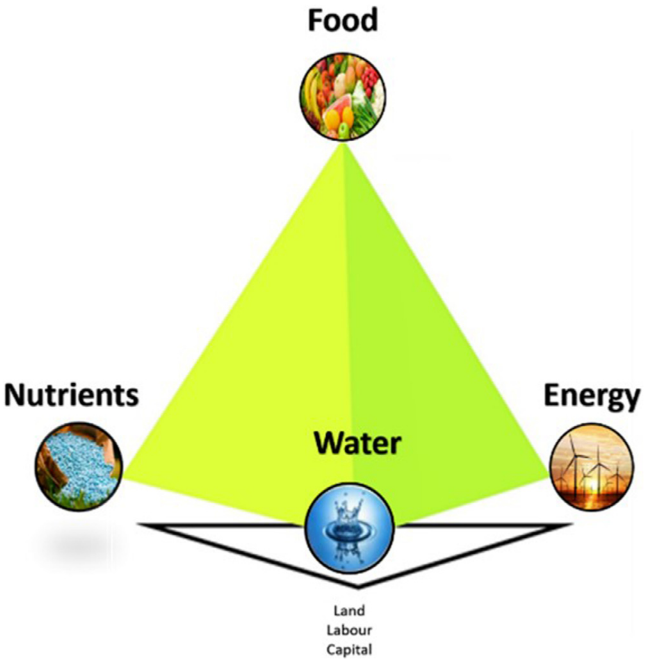

Fig. 1. WENF nexus pyramid with the circles at the vertices representing resource stocks and the edges of the pyramid representing nexusinteractions [13].

Methodology

For this analysis, three urban farms were examined: a rooftop greenhouse situated on top of a large hotel in Amsterdam (the Netherlands) and an open field community farm and a commercial container farm in Boston (MA, USA).

Boston – community farm (Eastie farm)

This community farm is run by volunteers, making use of low-cost production methods like raised beds (Fig. 2).

Boston – container farm (corner stalk farm)

A high-tech commercial farm operated in four shipping containers, with vertically positioned towers (Fig. 3). Only one out of its four containers is used as case study site, as the containers are comparable in production and thus in resource use. Using a configuration with vertically positioned towers on 35m^2 of land, 78 m^2 (840 ft^2) of growing surface is created per shipping container. The plants are grown in the horizontal direction, at a 90-degree angle with the ground surface, using a hydroponic system. The soil is replaced by rock wool. Consequently, all the nutrients that crops require must be added through fertilizer additions in the irrigation water.

Amsterdam – rooftop greenhouse (QO hotel)

On the roof of a hotel in Amsterdam, 76 m above street level, a greenhouse was installed with state of the art hydroponic and vertical farming technology. Although the QO hotel aimed to produce year-round, the absence of data on continuity of crop production during winter resulted in the assumption that no crop production took place from November up till April. A monitoring and control system for horticulture (Priva) continuously monitored numerous resource parameters in the greenhouse (Fig. 4).

The three case study farms are characterized by different objectives, various modes of operation, diverse ways of securing supply and addition of resources and a multifarious set of crops that they grow. Analysing different systems in different cities and countries allowed the study of the influence of different circumstances, various farming policies and diverse engineered systems on the connection between the urban waters and the energy, nutrient and water demand of the farms.

Resource consumption at three urban farms

Field data were collected on water, energy and nutrient consumption at each of the urban agricultural initiatives. The energy component includes power consumption from the grid and solar radiation. The nutrients that were considered are nitrogen, phosphorus and potassium because food production depends on these macronutrients.

The procedure for data collection and data analysis depended on the technical installation, mode of operation and available crew at each case study site and was therefore executed in a widely different way at each farm (see Table 1).

Staff of the case study sites was involved in data collection, not only to read the meters on site, but also to collect and record information of their operation system and resource supply chain.

As this research did not collect demand data year-round, but aimed to simulate the potential water storage over a multi-year timespan, the average water demand during the field study was used as water demand input for days outside the field study period. This required the assumption that the same crops were grown, in the same ratios, during the entire growing season, under the exact same climatic circumstances as

Fig. 2. Eastie Farm: community farm using raised beds.

Fig. 3. Corner Stalk Farm: Container farm using LED lights to vertically grow crops indoors.

Fig. 4. QO hotel: Rooftop greenhouse.

during the study period. At the container farm, this assumption seemed reasonable, as the vast amount of LED lights provided enough heat to grow crops even during the coldest months and no use of natural sunlight was made; the reduction in daylight hours during winter did not affect crop production. However, weather conditions have a substantial impact on crop water needs in greenhouses and open field farms. In times of lower outside temperatures and less daylight hours than during the study period, plants transpire less. Since the average water demand measured during the summer was used as a water demand input for spring and fall, the water consumption during those seasons is likely overestimated.

Resource availability in vicinity of case study farms

Besides investigating the water, energy and nutrient consumption at the urban farms, this study also aimed to provide insight in the availability of these resources in and near the farms to examine the feasibility of connecting the urban agricultural industry and the wastewater sector. This was done by examining the potential for local rainwater and sewage harvesting. As will be shown in the subsequent analysis, data limitations do not really let firm conclusions be drawn about the feasibility of this concept, but instead illustrate the actual potential at these sites and allow further reseach needs to be determined.

Sewage water availability

Waternet, which is the local water authority in Amsterdam, and the Massachusetts Water Resources Authority (MWRA) in Boston shared information on the wastewater quality. In neither of the two cities water authorities monitored the wastewater flows and water quality in sewer pipes at a local level. Therefore, local sewage availability could only be estimated based on numerous assumptions. This back-of-an envelope analysis, however, showed promising results on nutrient and energy availability in sewage, underlining the need for better data.

From the sewer layout maps the number of upstream connections from the point nearest to the urban farm under investigation could be identified. As it was not clear to which parts the sewer was connected outside of the sewer maps that were provided, it was decided to conduct this study using only the upstream connections visible on the maps to prevent an overestimation of resource availability. With the help of some generic and demographic information, such as the average daily water consumption per person (107 L per capita per day in Amsterdam and 155 L per capita per day in Boston [30]; MWRA, 2016), and the average number of people per household (on average 2.36 persons in Boston [27]), the local average dry weather flow in the Boston public sewer could be estimated. In Amsterdam the internal wastewater production of the hotel was approximated based on the total number of rooms and their occupation rate. When assumed that half of the rooms were permanently occupied with a least one guest, sanitary waste from a minimum of 144 people was considered capturable.

Nutrient availability in sewage

Multiplying the average concentration of a nutrient in the sewage by the daily water volume passing through the sewer near the case study site resulted in the average total available daily nutrient load.

Nitrogen uptake by plants mostly occurs through nitrate and ammonium. Therefore, those are the only two nitrogen forms that are considered during this analysis. Phosphorus calculations depended on the available data. In Amsterdam only information on the total phosphorus

Table 1
Description of the resource provision, monitoring system, data collection and analysis at three case study farms.

	Boston		**Amsterdam**
	Community farm	**Container farm**	**Hotel greenhouse**
Water system	Rainwater is collected from neighbouring roofs and stored in rain barrels, through gravity flow. Volunteers drain water from the barrels and carry water to the crops. Water is also used for sheet mulching and washing hands	A garden hose connected to a nearby tap delivers water to the storage barrel. Water is pumped towards the top of the vertical crop towers, where it is released and distributed downwards by gravity. Water that has not been used by crops is collected at the bottom of the towers and recycled. Condensed water captured at the air-conditioner is returned to the irrigation system	After reverse osmosis treatment of stagnant water from unoccupied hotel rooms, irrigation water is pumped to the hotel's rooftop. The irrigation system recycles water by recapturing water that trickled past the crops through the hydroponic gutters
Water monitoring	Water consumption data were measured by digital garden hose water meters (RainWave RW-9FM) that were read each day that water was withdrawn from storage barrels by farm volunteers. It was assumed that the plants weren't watered on days that no data were collected in the online spreadsheet	A digital garden hose water meter, a RainWave RW-9FM, measured the cumulative flow every time the water storage barrels were filled	An automatic computer operated system with Priva software collected data on the water volume flowing through each subsystem. Because of internal recycling, the water count outnumbers the consumed water volume by plant uptake
Water calculations	Water uses from all five rain barrels were totalled	Average daily water use was calculated from irregular readings by dividing the added water volume by the number of days between the recording and the previous time water was supplied to the storage system	The head of greenhouse operations estimated the water efficiency of the greenhouse to be around 95%. This meant that 5% of the circulated water count was considered to comprise water consumption
Energy system	No electrical use on site. Sunlight provides solar radiation	A pump, 70,000 LED lights providing blue and red light and air conditioning all consumed electricity	Energy consumers include lights, the computer control system, reverse osmosis treatment and pumps. Energy is supplied through solar radiation, heating and electricity
Energy monitoring	Collection of energy data is not applicable, since no electricity is used for crop cultivation, irrigation and maintenance at this case study site	An analogue meter (Baodain single phase three wire energy meter) was installed by an electrician and was read regularly to note interim values	The hotel's weather station collected solar radiation data. Energy use for heating and power for lighting was recorded by the computer system, just like the solar radiation blocked from entering the greenhouse by curtains. All energy data were automatically collected with a 5-minute time resolution. No data are available on the energy consumption of the operating computers, reverse osmosis treatment and pumps.
Energy Calculations	Does not apply	Average daily energy use was calculated from irregular cumulative readings	The electric power consumption for 12 5-minute intervals per hour, 24 hours per day were added. By multiplying the solar radiation by the roof's window surface (230 m^2), and subtracting the blocked radiation, the total net incoming radiation was computed. The potential energy requirement to operate the pump transporting water from the basement towards the greenhouse was estimated by multiplying the building height by the weight of the consumed water
Nutrient system	Compost from domestic food scraps and industrial sawdust, is produced on site in three composting containers	Synthetic fertilizer (see specification in appendix 1a) is dosed automatically based on the electric conductivity (EC) of the irrigation water	Synthetic nutrients are applied through an automated dispenser based on EC measurements. Organic fertilizer is added manually based on visual inspection of the crops. Fertilizer specification is displayed in appendix 1b
Nutrient monitoring	Fertilizer was added as compost. Volunteers kept tally of the number of added 5-gallon buckets	Fertilizer use was monitored by weighing dry fertilizer before adding it to the system as a solution.	The daily consumption of artificial fertilizer was acquired from the automated monitoring and control system. The volume of added organic fertilizer solution was measured geometrically using a ruler around the jerrycan packaging

(*continued on next page*)

Table 1 (*continued*)

	Boston		Amsterdam
	Community farm	**Container farm**	**Hotel greenhouse**
Nutrient Calculations	Nutrient additions were calculated using a specific density of 0.39 g/cm^3 for compost [22] and a composition of 1.6% nitrogen, 0.6% phosphorus and 1.4% potassium for a compost mixture of food waste, mature compost and sawdust [19]. The density, added volumes and compositional percentages were multiplied	Mass percentages of both elemental phosphorus and potassium were derived from the table of constituents and molar mass calculations (see appendix 1a). The dry fertilizer weight was multiplied by these percentages in order to calculate the weight of each element that was supplied to the crops	Applying a molar mass calculation, resulted in the concentration of the three nutrients in the synthetic fertilizer (appendix 1b). Multiplying these concentrations by the amount of added fertilizer solution resulted in the final dry weight of fertilizer consumption. To prevent inconclusive measurements from skewing the data, it was decided to leave data collected over an incomplete runtime (less than a full day) out of consideration. For the organic fertilizer the upper composition limit on the packaging label was used to calculate the nutrient use. Presuming that the percentages on the packaging were the mass fraction, they were multiplied by the total consumed solution volume and by the density of the solution (1300 g/L). This resulted in the mass of the molecules carrying the nutrients. A molar mass calculation was then executed. The consumed mass of the molecule was then multiplied by the mass ratio to obtain the mass of the elemental nutrients in the solution and averaged over time
Food system	A variety of crops (from vegetables to pears and berries) is grown Growing season lasts from April 7 till November 7	Year-round food production cultivating crops that can resist gravitational pull, like basil, different types of lettuce, tomatoes and green onion. Each tower generates harvest eleven to twelve times a year	Food is grown in four subsystems, growing a total of 40 to 50 different crops, ranging from liquorice basil to cherry tomatoes and from edible flowers to mint. A growing season in the greenhouse was projected to last from the 1st of April until the end of October
Food monitoring	Annual yield is recorded manually	Average weekly yield is estimated	Daily yield is recorded manually

concentration was provided and therefore used in the nutrient availability analysis. Part of the phosphorus is however bound to other components and therefore more difficult to harvest. Hence in Boston, where data on the concentration of the solvable compound ortho-phosphorus were provided, this concentration was used during the calculations.

Sewer operators of both cities did not measure potassium concentrations in the influent of treatment plants. Therefore, an analysis on the availability of this nutrient was omitted.

Energy availability in sewage

The chemical energy content of the sewage is estimated to be 12.5 MJ/kg COD [28]. This energy can be released with a 100% efficiency for heat production. At Corner Stalk Farm and for certain activities at the QO hotel, however, electricity is consumed. In those cases, a biogas generator would be required to transform the energy into electricity. Since those generators typically run at 35% efficiency, one kilogram of COD can only be converted into 1.2 kWh of electricity.

Rainwater availability

In order to calculate the rainwater availability near the case study sites, rainfall data collected by local authorities were downloaded. To make sure that the analysis is based on the latest rainfall patterns, a precipitation analysis period of 20 years was targeted. A longer rainfall analysis period would only increase the quality of the statistics, but was not thought to provide a more realistic picture on the current climate and rainfall situation.

For Amsterdam an uninterrupted sequence of daily sums of precipitation at Amsterdam Airport Schiphol was downloaded for the period between January 1, 1999 and December 31, 2018 [16]. The precipitation data for Boston Logan Airport were downloaded for the same time span from the website of the National Weather Service Forecast Office [23]. Two days, August 23 and 24, 2003, are missing in the sequence. Traces of rain defined as < 0.01 inch/day in Boston and < 0.1 mm/day in the Netherlands were neglected.

To obtain information on the available rainwater volume it was decided to multiply the rain depth only by the roof area of the greenhouse and the container respectively. In the case of Eastie Farm, which does not own a roof for water collection, the total roof surface area of adjacent parcels in the block was determined. According to Lancaster [18] only 80 to 85% of rainfall on flat roofs results in runoff. For pitched roofs this percentage is slightly higher (90%). To correct for this loss, rooftop areas under investigation were multiplied by the corresponding runoff coefficient to calculate the effective surface, which could be multiplied by the rainfall depth in order to determine the potentially available rainfall volume that the rooftops could generate.

At Eastie Farm the rainwater collection area that is required to match water demand and supply year-round in all the 20 years for which rainfall data were analysed was dimensioned by minimizing the difference between harvested rainwater volume and water use at the farm. This was done under the assumption that water demand took place between April 27 (first day water demand was recorded) till November 7 (the last day of the frost-free growing season), whereas rainwater was collected year-round. A similar analysis was not carried out for the other farms, since those could cope with their own roof surface to provide for their water demand.

Comparison of water supply and demand

Both the average use and peak demand of nutrients and energy were compared to the available amounts in sewage. For water, a slightly more complex approach was applied.

Daily water demands were subtracted from the rainfall volumes falling on the catchment area, showing whether that day would experience a water surplus or a shortage, which would be translated in an increase or a reduction of the continuous storage assumed to be located at each site. Due to time limitations, real-time water demand data were only recorded during the 2018 growing season. These demand data were used for all years under investigation. Outside that time frame, the average water use of the study period was used to simulate fluctuations in available storage volume year-round. A continuous water balance simulation was made in a spreadsheet, using the following formula:

$$\begin{aligned} \mathit{Storage}(t) = \mathit{IF}(((&\mathit{Storage}(t-1) + \mathit{daily\ change\ in\ storage}) > \\ &(\mathit{Maximum\ Storage\ Capacity})); \mathit{Maximum\ Storage\ Capacity}; \\ &(\mathit{Storage}(t-1) + \mathit{daily\ change\ in\ storage})) \end{aligned}$$

To overcome any dry periods at the start of the growing season, the storage tanks were simulated to be filled from January 1999 on with rainwater falling on the selected collection surfaces. At Corner Stalk Farm the water demand was continuous, without seasonal pauses, while water demand at Eastie Farm was assumed to start at April 28, lasting until November (mimicking the local growing season). The growing season in the Netherlands starts the 1^{st} of April and lasts until the end of September, totalling 183 days. However, due to the more optimal growing conditions in a greenhouse, for analysis it was assumed that crops could be grown between the 1^{st} of April and the end of October.

Ultimately, the storage volume required to optimally use the water harvested from the selected surfaces was determined. This was done by establishing the largest decline in continuous water storage over each of the 20 years analysed and based on the principle that the total volume was never allowed to run dry.

Water efficiency

For both Corner Stalk Farm and Eastie Farm the water efficiency of the operation was calculated. A similar analysis could not be done for the greenhouse in Amsterdam, as data about theoretical resource needs for the rare crops grown at the QO hotel were not available.

In order to determine the water efficiency, the daily transpiration rate was calculated using the Blaney-Criddle method [10]. For this method, the mean daily temperature (T_{mean}) was determined at the Boston Logan Airport NWS weather station, followed by the determination of the mean daily percentage of annual daytime hours (p-factor), which ranged between 0.30 and 0.34 [10]. LED lights at Corner Stalk Farm provide light to the crops 24/7 and plants transpire the entire nychthemeron. Therefore, a p-factor of 1.0 was used to calculate the daily transpiration at the container farm. The crop factor (K_c) was then used to determine the transpiration for each crop type in each growing stage at Eastie Farm (Appendix 5a; [10]). Because of the continuous production at the container farm, the weighted average of the crop factor for the shortest lettuce (greens) growing cycle was calculated ($Kc = 0.68$) and used in further calculations. At Corner Stalk Farm the total (evapo-)transpirated volume was calculated by multiplying the required water depth for lettuce by the total growing surface of 78 m^2. At Eastie Farm, where crops are grown in mixed beds, the exact surface used by each crop was unknown. Therefore, the surface area was approximated using the average yield density in the United States [9] combined with yield weight data for each of the cultivated crops at the farm (Appendix 5c).

The total required water volume for crop transpiration was then compared to the total water supply to the farm (both rainfall and manual application at Eastie Farm and automated supply at Corner Stalk Farm) in order to calculate the efficiency of the water supply.

Results

Eastie farm

Open field community garden Eastie Farm in East-Boston had many systems in place to facilitate sustainable food production.

Required resources

Eastie Farm did not make use of any electrical equipment and therefore has no artificial energy requirements. Water and nutrient additions were recorded on location.

Water. Water is supplied by precipitation falling on the fields and by manual irrigation of water captured on neighbouring rooftops (Fig. 5) and stored in rain barrels.

During the complete data collection period from April 28 till August 17 - a timeline that does not cover the entire growing season - in total 10,300 L of precipitation watered the beds and 7,900 L of water were supplied manually. Water was supplied manually with great regularity to sustain the crops, with a daily peak supply of 750 L at the start of the season.

During extended periods of drought, like from mid-June till mid-July, the farm depended on stored water from the rain barrels and the manual watering frequency was higher than during times with regular and sufficient rainfall. However, watering was not completely synchronized with the weather situation, as there does not seem to be a correlation between the number of days since the garden last received rain and the amount of water that was added during a watering session.

Nutrients. Compost was added irregularly and only at three occasions during the data collection period. It totalled 95 L (25 gallon), estimated to contain 591 g of nitrogen, 222 g of phosphorus and 517 g of potassium. On average, this is 5, 2 and 5 g of nitrogen, phosphorus and potassium respectively daily during the entire data study period, whereas the maximum daily compost supply consisted of 355 g of nitrogen, 133 g of phosphorus and 310 g of potassium.

Available resources

Local precipitation patterns and sewage parameters were studied to determine the local availability of resources.

Precipitation. For open field culture the growing season starts at April 7 and finishes at November 7, lasting 214 days. The amount of rainfall during that period varied between 391 mm (2016) and 945 mm (2006) and averaged at 631 mm per season. At the farm itself, 29.7 m^2 of raised beds were created to grow crops. Besides the raised beds, within Eastie Farm's housing block 50 m^2 of pitched roofs and 230 m^2 of flat roofs were deemed suitable for rainwater collection.

Sewage. A total daily dry weather flow of 42.8 m^3 was estimated to flow through the sewer pipe in front of Eastie Farm [13]. Data on the sewage quality in this system are shown in appendix 3a. It is found that the wastewater influent contains on average 21.6 mg/L of ammonium, 0.25 mg/L of nitrate and 2 mg/L of dissolvable orthophosphates. Unfortunately, no data were provided on potassium presence in the sewage. The average chemical oxygen demand (COD) amounts to 399 mg/L. The average daily nutrient loads in 43 m^3 of this sewage are 924 and 86 g for ammonium and orthophosphates respectively, equalling 718 g of nitrogen and 28 g of elemental phosphorus, given their mass ratio in the aforementioned molecules.

Match requirements and availability

Water. The rainwater collection area that is required to match water demand and supply year-round is called the break-even surface. The break-even surface for Eastie Farm amounts to 154 m^2. Raised beds combined with nearby rooftops can provide for this surface.

Fig. 6 shows that (when a sufficiently large catchment surface is connected to the storage) most seasons end with significantly more water in storage than they had at the start of the season. This shows that not the entire rainfall harvesting capacity needs to be stored to sustain crops during dry periods. When a continuous simulation is made for the storage during the year, it becomes evident that the storage capacity required to overcome the largest decline in potential storage, which occurred in 2016, amounts to 6800 L of water. In short, Eastie Farm can benefit from a significant expansion of the rainwater storage capacity (currently around 1040 L) to avoid water shortages.

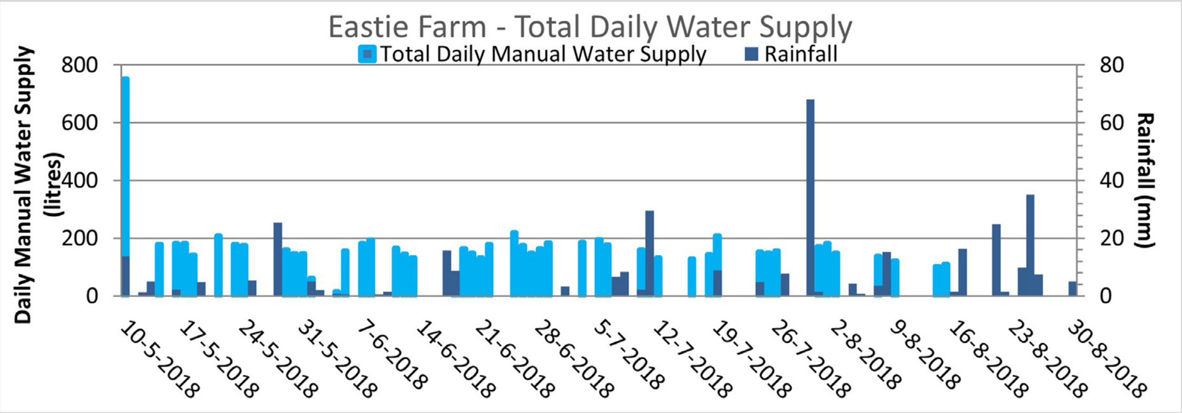

Fig. 5. Rainfall and manual water supply to Eastie Farm during data collection.

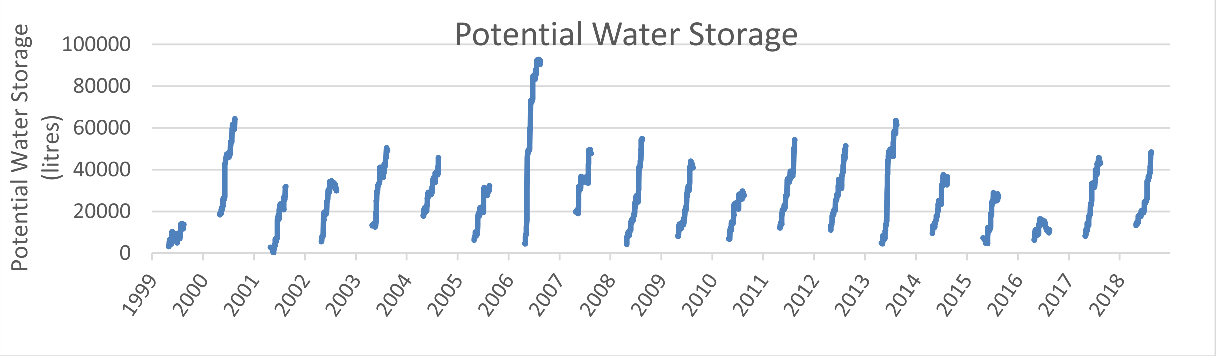

Fig. 6. Potential rainwater storage using a break-even surface of 154m^2 for rainwater collection. Data run from April 27 till August 17 every year. The offset of each line represents the potential storage build up since April 7 each year.

Nutrients. Sewage can ensure an ample supply of nitrogen and phosphorus to Eastie Farm's community garden. Average sewage flows can not only provide for the average daily demand of both elements, but for the highest measured daily consumption of 355 g of nitrogen too. Peak demands of 133 g of phosphorus, however, cannot be met by the wastewater stream.

As the wastewater influent at the central treatment plant contains on average 0.7 mg/L of phosphorus and 16.8 mg/L of nitrogen in several molecular configurations, the average daily nitrogen demand can be met by recovering nutrients from 300 L of sewage. Sufficient phosphorus recovery requires treatment of 2,860 L of wastewater daily (if 100% recovery can be assured), where 43,000 L are available.

Harvest and resource efficiency

Eastie Farm cultivates various edible crops ranging from fruits to vegetables and even herbs. In total 350 kg (770 lbs) of fresh produce was harvested. In appendix 4a the itemized seasonal yield is shown. Crop factors for transpiration at different growing stages could not be found for garlic, beets, kale, herbs, cherries, berries, pears, sprouts and cauliflower. Nonetheless, the efficiency analysis was executed for the remaining crops, which hold the majority of the yield weight (61%). However, the outcome of this efficiency analysis largely underestimates the efficiency of the farm, because of this assumption.

Water efficiency. Assuming crops were sowed on April 7 (immediately at the start of the frost-free growing season), the total theoretical (evapo-)transpiration depth ranged between 395 mm for spinach and 619 mm for dry onions (appendix 5b). To convert this transpiration depth into a transpiration volume, the cultivation surface for each crop had to be known. According to the FAO's yield density data, 91 m^2 of growing area is required to produce the garlic, cauliflower, carrot, pea, spinach, onion, lettuce, cabbage, squash and tomato harvest that Eastie Farm recorded [9]. This area exceeds the 29.7 m^2 of raised beds present at the farm by far, even though the area needed to grow beets, kale, herbs and sprouts is excluded because of the lack of FAO data. Therefore, it is safe to say that the crop density in the raised beds at Eastie Farm must have been higher than the average crop density of American agriculture.

The theoretical surface requirement per crop was scaled down by a factor 29.7/91 in order to approximate the true cultivation surface per crop. Using the scaled down surface areas, a total water need of 10,350 liters was computed by this theoretical approach.

During the same time period, on-site measurements showed that 7,921 liters of water were supplied manually by volunteers. Moreover, 10,312 liters of rain fell on the raised beds, which means that in total 18,233 liters of water were in fact supplied to the crops during the measurement period. All things considered, these data suggest a water efficiency of 57%, which should be a considerable underestimation given all the assumptions made.

An average water use of 52 L/kg of produce was recorded, which is considerably more efficient than the modelled water use of 250 L/kg that Barbosa et al. [4] suggest for conventional agriculture. All in all, the water supply at Eastie farm seems to be highly efficient for an open field farm. In fact, the water efficiency is so high, that one starts to doubt the records on manual water supply. Given the community operated nature of this farm, resulting in a vast number of volunteers helping to sustain the crops, it would not come as a surprise that not all water additions were registered.

Corner stalk farm

Corner Stalk Farm in East-Boston makes use of many high-tech techniques to facilitate optimal food production year-round.

Required resources

Water, energy and nutrients were all added to make the crops thrive.

Water. During the 117 days between April 21 and August 15, a total water consumption of 2,974 L was recorded at Corner Stalk Farm, resulting in a daily average of 25 L/d. Daily water consumption varied between 8.5 and 48.4 L/d, with outliers of 124 L/d during 3 days at the start of May. There is however a possibility that during the summer months water use was registered less consistently by the responsible volunteers. This could have resulted in an overestimation of the time between consecutive water replenishments, and consequently in an underestimation of the total and average daily water use over the summer.

Energy. During the 113 days that electricity use was measured at Corner Stalk Farm a single container consumed a total of 14,958 kWh. Over the course of the study period, the energy demand rose from 95 to 142 kWh/d, resulting in an average daily energy consumption of 131 kWh per container. Only at the start of May a small peak in daily energy consumption was noticed. Both this peak and the relatively high energy consumption during the last data stretch coincide with some very warm spring days with temperatures as high as 34°C (93F) and the generally warmer summer months respectively. Presumably, the increase of energy consumption during the season can be attributed to a larger electricity need for air conditioning. Moreover, the water consumption during these times was higher than average, resulting in higher energy needs to operate pumps. Energy requirements for lighting were fairly constant as the LED lights are switched on 24/7. A daily energy consumption of 23 kWh for the lighting at each container was calculated.

Nutrients. Data on the daily release of the nutrient dispensers were not available. Therefore, data on the replenishment of the dispensers were recorded, allowing to calculate the average daily nutrient supply in the time period between each refill.

During the data collection period, more than 2 kg of fertilizer were added to the container under investigation, including 214 g of nitrogen, 40 g of phosphorus and 361 g of potassium. The mean daily consumption of nitrogen, phosphorus and potassium amounted to 1.8, 0.3 and 3.1 g/day respectively, with maximum daily demand values of 7.9, 1.5 and 13.4 g/day. These peak demands coincide with the peak demand in water consumption.

Available resources

Both precipitation and (sanitary) wastewater could be used to meet agricultural water needs. However, because of its less polluted nature, rainwater is the preferred source for irrigation.

Precipitation. Corner Stalk container farm is growing crops year-round. An analysis on the total amount of rainfall during a growing season of 214 days, starting every month, shows that the relatively long duration of growing seasons combined with the relatively constant rainfall during the year seems to level out seasonal variation in precipitation, averaging around 644 mm. The rainfall patterns in East Boston are multiplied by a surface area of 35 m^2, corresponding with the size of a rooftop of a single container that served as rainwater catchment area.

Sewage. The volume of sanitary wastewater flowing past the farm was estimated to be 16 m^3/day [13]. This flow is underestimated as the sewer system extended further upstream than the data provided to the researchers showed. The wastewater from this area flows to the Deer Island treatment plant [20]. The wastewater quality of its influent is displayed in appendix 3a. However, the influent of the wastewater treatment plant also contains effluent from combined sewers, whereas the wastewater stream that is suggested to be tapped into for nutrient abstraction for Corner Stalk Farm consists of pure sanitary waste, resulting in a further underestimation of wastewater availability.

Nutrient availability in sewage. On average 348 g of ammonium and 32 g of orthophosphates are computed to pass Corner Stalk Farm daily, equalling 270 g of nitrogen and 9 g of elemental phosphorus.

Energy availability in sewage. Given the average daily COD load of 6,422 g present in the wastewater flowing past the farm, the potential daily biogas yield amounts to 2.2 m^3 of methane, which equals 80 MJ.

Match requirements and availability

Water. By subtracting the daily water demand from the daily rainfall, the daily change of storage was calculated using a continuous storage model. Real-time water demand data were recorded between April 21 and August 15, 2018. Outside that time frame, the average water use during the data collection period of 25.4 L/day was used to simulate fluctuations in available storage volume year-round. By calculating the largest decline in potential storage that occurred during the assessment period, it was demonstrated that a storage volume of 1,177 L (311 gallon) was sufficient to overcome the greatest drought in the 20-year study period (Fig. 7).

The required storage volume suggests that no additional storage space is needed at the container farm, when a connection is be made between the existing storage barrels (1,250 L in total) and the container rooftop. However, the water demand data used during this assessment are questionable and it is plausible that the rainwater storage needs to be larger than noted.

Energy. Corner Stalk Farm gets all its energy delivered through electricity and therefore a typical biogas generator efficiency of 35% to transform the gas into electric power needs to be applied. The COD present in the wastewater near Corner Stalk Farm – of which the volume is likely generously underestimated as a result of lacking sewer layout data – has the potential to generate 7.8 kWh per day for the farm to use. One of the four containers on the farm's premises already uses far more than that (131 kWh/d on average). Therefore, it can be concluded that the wastewater stream as analysed in this study cannot provide enough energy to operate one – let alone four – container farm unit.

Nutrients. The entire fertilizer consumption can be met by sewage flowing past the farm, even though the nutrient load in the target pipeline is likely to be considerably underestimated. Given the modest fertilizer additions in the container farm, per container, only about 110 L of wastewater need to be treated daily (at a 100% efficiency) to recover sufficient nitrogen, whereas 460 L of sewage are required to supply enough phosphorus to meet a single container's demand.

Harvest & resource efficiency

Corner Stalk Farm grows more than twenty types of lettuces and a variety of herbs and other leafy greens (see appendix 4b). The farm records a harvest equivalent of 600 to 1000 heads of lettuce per container per week depending on the size of the heads. The growing cycle of cultivated crops lasts 42 -56 days, which is shorter than the 75 to 140 days growing period of lettuce that the FAO indicated [11]. The corps at Corner Stalk Farm however have constant light supply.

Water efficiency. A total theoretical (evapo-)transpiration depth of 1364 mm is computed over the entire measurement period. Given the growing surface of 78 m^2 per container, this results in a total water need of 106,400 liters. Although the application of the Blaney-Criddle method could have overestimated the transpiration rates and/or the lettuce types grown at Corner Stalk Farm could have been less water intensive than the generalized FAO data suggest, it is believed that this outcome provides a reliable view on the theoretical water needs of the container farm.

The farm only consumed 2,974 liters of water during the same time frame, which would mean that 2.8% of the transpired water escaped from the container system and 97.2% of the transpired water vapor was captured by the air conditioning and fed back to the crops. Moreover, these data do suggest an average water use of 0.7 L/kg of lettuce. This is way more efficient than either the hydroponic water use of 20 L/kg Barbosa et al. [4] computed or the average global water footprint for lettuce of 237 L/kg [21].

It is, however, presumed that the water demand data registered during the data collection campaign paint a picture which is rosier than reality, as water abstracted from the system by harvesting crops, seems to have exceeded the total registered water consumption. Baras [3] stated that hydroponic lettuce heads rarely weigh over 0.3 kg (10 ounces). Assuming an average weekly harvest of 800 heads of lettuce, about 240

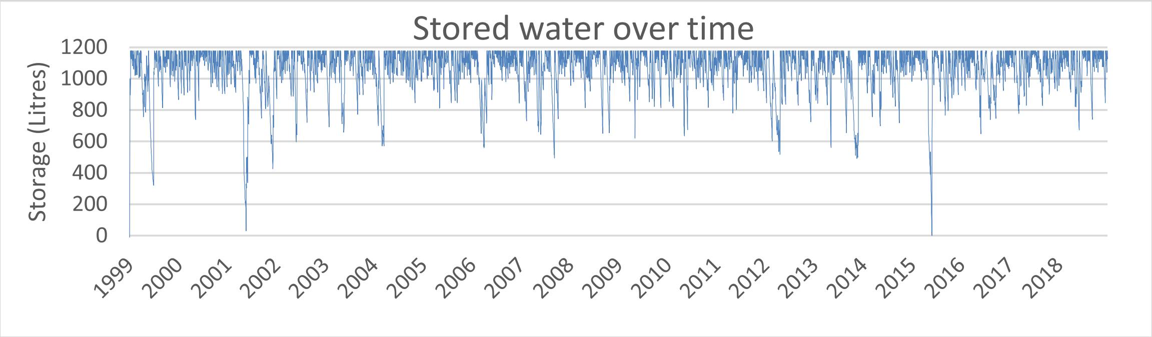

Fig. 7. Stored water over time at the container farm, based on a catchment surface of 35 m^2 and maximum storage volume of 1177 L.

kg of lettuce could have been harvested every week. Over the entire period of 117 days (16.7 weeks) that water measurements were conducted, this would result in a maximum production of 4,000 kg of lettuce heads. Given the typical water content of lettuce of 94%, this would mean that about 3,768 L of water could have been removed from the system by harvesting the crops [6]. The registered water consumption during this time was however no more than 2,974 L. Although it is possible that lighter heads were harvested, these findings raised suspicion that not all water additions were recorded.

QO hotel

The rooftop greenhouse of the QO hotel in Amsterdam makes use of many high-tech techniques and a combination of natural, organic and artificial resources.

Required resources

In the QO Hotel in Amsterdam measurements were done on all three resources under investigation.

Water. After a start-up period, the greenhouse shows a fairly constant daily water demand (appendix 2.3a). An average of 0.48 m^3 of water is consumed per day, assuming a 95% efficiency of the water circulation system. Given the brand-new, state of the art greenhouse, this is a conservative estimate, as some suppliers of recirculating hydroponic systems claim their system loses significantly less to evaporation [5]. At the end of July, a slight increase in water demand is noted when the fourth subsystem was employed to expand the horticultural production. The highest daily demand during the measurement period, which took place between July 6 and August 23, was recorded at 810 L/day.

Energy. Solar radiation is by far the biggest supplier of energy to the greenhouse with peaks at 1,880 kWh/d. Even on the darkest, cloudiest day recorded, solar radiation outnumbered all other energy sources. The LED lighting was tuned to the specific wavelengths that the crops need and their electrical power only amounted to 105 kWh/day on average (with a peak demand of 135 kWh/day). Average daily heat delivery from April till August was 31 kWh. Contrary to the energy consumed by lighting, the heat supply was highly variable, ranging between 0 and 170 kWh per day. The energy demand to boost water up to the hotel's rooftop would range anywhere from 0.05 to 0.17 kWh per day, depending on the water use. However, this is a considerable underestimation due to the unknown pump efficiency.

Nutrients. During the measurement period of 54 days, 2,935 g of nitrogen, 3,265 g of potassium and 513 g of phosphorus were added to the greenhouse, either in the form of artificial fertilizer or through an organic nutrient solution.

The artificial fertilizer was the sole nutrient supply to the crops for the first 5 days of the study. During this time 41 g of nitrogen, 45 g of potassium and 10 g of phosphorus were added. A gradual transition of 21 days took place during which both artificial and organic fertilizer were supplied to the water circulation system. It was during this time that the highest daily artificial fertilizer feed of 12 g of nitrogen, 13 g of potassium and 3 g of phosphorus was recorded.

In total 2,894 g of nitrogen, 504 g of potassium and 3,219 g of phosphorus were added through the organic fertilizer solution, resulting in a daily average of 58 g of nitrogen, 10 g of phosphorus and 64 g of potassium.

The best estimate of the highest possible daily fertilizer demand was made by adding the calculated average daily organic fertilizer consumption and the recorded maximum daily artificial fertilizer supply. This resulted in a daily peak demand of 70 g of nitrogen, 13 g of phosphorus and 77 g of potassium.

Available resources

Precipitation could have provided enough rainwater to the Amsterdam rooftop farm to accommodate the irrigation demand. Therefore, water in the form of wastewater will only be analysed as a source of energy and nutrients, but will be left out of consideration during the water availability discussion.

Precipitation. Annual rainfall in the Netherlands was 860 mm on average the last 20 years, with 2018 being the driest year (559 mm) and 2000 being the wettest (1054 mm). On average, spring is the driest season. Summer and fall are considerably wetter. In 2007, the largest dry spell in the data series under investigation was recorded, lasting 44 days from March till May.

The outdoor growing season in the Netherlands lasts for 183 days between the 1st of April and the 30th of September. The amount of rainfall during that period varies between 288 mm (2003) and 561 mm (2007) and averaged at 438 mm per season. However, the greenhouse on top of the QO hotel expected to be able to grow crops during a larger part of the year.

Water availability through precipitation. Because of the research's perspective at resource demand and availability through a WENF nexus lens, it was decided to consider the greenhouse's rooftop (230 m^2) as the only rainwater catchment area in the rainwater availability analysis. The water availability assessment showed that on the glass roof surface of the greenhouse, yearly, an average rainfall volume of 178,000 L can be caught.

Sewage. When assumed that half of the 288 hotel's rooms are permanently filled, at least 15.4 m^3 of wastewater is available for nutrient and energy recovery every day [13]. Data on the sewage quality at the Treatment plant West where wastewater from the Amstelkwartier is treated is shown in appendix 3b. The wastewater influent contains on average 62 mg/L of nitrogen and 8 mg/L of dissolvable phosphorus. The average chemical oxygen demand (COD) is 613 mg/L. No data were provided on potassium presence in the sewage, nor on the concentrations of different molecules containing phosphorus and nitrogen. It was assumed that all forms of nitrogen and phosphorus in the sewage could be recovered.

Energy availability in sewage. On average, 9.4 kg of COD flow through the hotel's pipelines daily. Hence, the potential daily biogas yield of

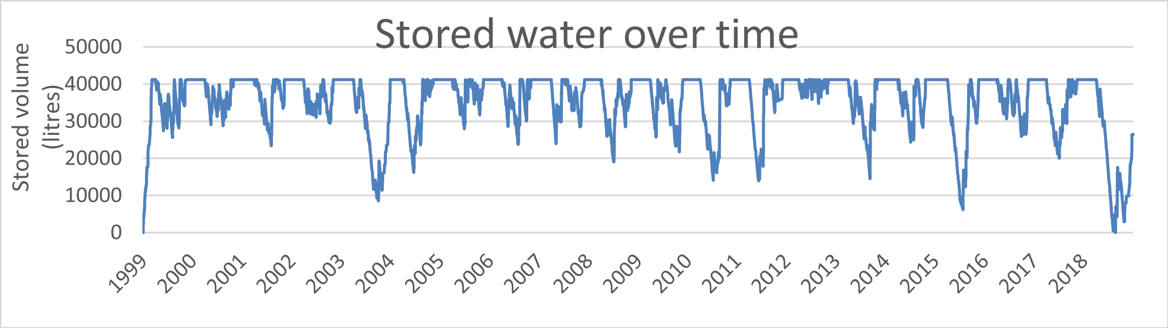

Fig. 8. Potential water storage over time at the rooftop greenhouse when connected to a storage basin of 41.2 m^3.

wastewater generated in the hotel amounts to 3.3 m^3 of methane, which equals an average energy content of 118 MJ/day.

Nutrient availability in sewage. The average daily nitrogen load from the hotel's wastewater flow amounts to 955 g. Daily phosphorus loads are around 123 g. Because of the discrepancy between the average daily concentrations of constituents at the central treatment plant and the concentrations of a constituents in a purely sanitary sewer or collection pipeline inside the hotel, the computed nutrient load near the hotel is likely underestimated in this analysis.

Match resource requirements and resource availability

Water. For a growing season between April 1 and October 31, the 230 m^2 greenhouse roof had to be connected to a storage volume of at least 41,235 L, so that there would be no water shortages (Fig. 8).

Energy. Given the efficiency rates of biogas conversion to heat and electric power respectively, the greenhouse requires 112 MJ for heat supply and 1080 MJ for electricity production on an average day in summer. Light demand peaked at 1389 MJ per day and the maximum daily heat demand was 612 MJ, however those maxima are unlikely to coincide. Hence it can be concluded that the energy content from biogas harvested from wastewater of a semi-full QO hotel only contains enough energy to accommodate 10% of the energy consumption of the rooftop greenhouse in summer.

Nutrients. The hotel's wastewater can deliver the average daily nutrient needs, but also the highest daily fertilizer addition registered (70 g of nitrogen and 13 g of phosphorus).

Harvest & resource efficiency

The QO greenhouse grows a wide selection of crops for the hotel's kitchen, ranging from cherry tomatoes, eggplants and cucumbers to rare and exotic crops like nasturtium flowers, oyster leaves and liquorice basil. All fruits, vegetables, leaves and flowers that were harvested were recorded by the cooks of the hotel in a logbook to hold track of the yield. This logbook is displayed in appendix 4c.

Plant mortality in the extremely warm summer months was rather high, as the water temperature in the greenhouse system exceeded the acceptable range and lots of plant roots died. Perished plants did not result in any harvest, although they were fed resources earlier in the season, skewing the resource need per yield unit throughout the season. One of the explanations for the reduced resource input during the last weeks of the data collection period is simply that not all dead plants had been replaced yet.

Water efficiency. Theoretical resource requirements for most of the produce grown in the greenhouse are difficult to find in academic literature as the greenhouse does cultivate many uncommon crops. As a result, no reliable water efficiency analysis could be executed.

Discussion

Urban farming comes in many shapes and forms. During this study we had a look behind the scenes at a wide variety of farms at different locations worldwide. Despite all uncertainties in the analysis an effort was made to map the potential for water, energy and nutrient recovery from urban waters to meet the resource demand for food production at each case study farm (Table 2).

The differences between the three urban farms in terms of potential for circularity and current resource efficiency are enormous. The (commercial) indoor farms employ highly efficient techniques to arrange water, nutrient and energy supply to their crops. Many of those techniques, however, supply artificial resource input to the crop cultivation process, whereas, from a WE(N)F-nexus perspective it would be recommendable to make use of as many natural sources of light and heat as possible. Therefore, given the assumptions made in this analysis, it can be concluded that the water and nutrients for urban food production are abundantly available in Amsterdam and Boston and so is sunlight energy. Only if an around-the clock and all-season food growing process, such as at the container farm, is utilized substantial electric power is needed for artificial light, cooling, heating, pumps, monitors and controllers. These case studies potentially show that creating a closed loop resource system by local food production seems feasible if not pushed to the edge of a maximized, 24/7 agricultural operation. The research did, however, identify several issues that need to be further examined to strengthen these conclusions.

Issues with data collection during this study

Acquisition of quality data poses the biggest challenge in WENF nexus research. The absence of data collected at the urban level and the fact that data are scattered under the jurisdiction of private commercial organisations and various departments of local, provincial and even national institutions, result in incoherent information. This challenge has been mentioned too by other authors [7,24].

Even though this study aimed to close gaps in the WE(N)F nexus quantification, a critical reflection indicates that not all data collected in this study are sufficiently reliable to contribute to solid quantitative recommendations on the feasibility of closing water, energy and nutrient loops for urban farms and the integration of urban waters and urban agriculture (see Table 2).

Resource consumption data

The issues encountered during the data collection varied from site to site. Different modes of operation, technological advancement and farming staff resulted in diverse challenges during the measurement period.

Water. At Eastie Farm, the water data collected by a designated volunteer who watered plants were assumed to be adequately accurate and complete. However, water abstractions by other volunteers, who despite notification signs were not informed about the ongoing data collection, might not have been counted in, making the general accuracy of water use unknown.

At Corner Stalk Farm an impossibly high efficiency was recorded, as the water content in the harvested crops seems to have exceeded the

Table 2
Quantitative summary of case study findings on water, energy and nutrient demand at farms and their availability in urban waters.

	Energy			**Nutrients**			**Water**			
	Average Artificial Demand *(/day)*	**Availability** *(/day)*	**Match***(%)*	**Average Demand** *(grams/day)*	**Availability** (grams/day*)*	**Match** *(%)*	**Demand***(m^3/ year)*	**Availability***(m^3/ year)*	**Match***(%)*	**Efficiency***(%)*
Community Farm	0	N/A	N/A	N: 5 P: 2 K: 5	N: 718 P: 28 K: N/A	100	18	19	100	57
Container Farm	131 kWh	7.8 kWh	6	N: 2 P: 0.3 K: 3	N: 270 P: 9 K: N/A	100	3	23	100	97
Greenhouse	1,192 MJ	118 MJ	10	N: 54 P: 61 K: 10	N: 955 P: 123 K: N/A	100	88 (= 0.48 * 183)	178	100	N/A

total water input at the farm. Therefore, it is concluded that at least some water consumption data must be missing from the collection series, and consequently, that the water data measured at this site are unfit to carry out a reasonable analysis.

At the QO hotel a computer operated system controls and monitors the water circulation through the greenhouse. However, since a water circulation system was installed a part of the water fed to the crops passes through the water meter several times. Therefore, an approximate assumption had to be made on water circulation efficiency, which could have skewed the results significantly.

Another uncertainty factor is that due to project limitations the measurement period for all three case study sites was confined to only a few months. To generate an approximation of the yearly demand, the average water demand measured during the measurement period was used for dates outside this measurement period. Water demand can, however, significantly vary throughout the year, potentially leading to either an underestimation or overestimation of the required storage volume.

Energy. The average daily energy use calculated for Corner Stalk Farm is thought to be accurate and complete, as a cumulative energy consumption meter for the entire container unit was installed and read, allowing for accurate averaging.

The recorded energy consumption data of the QO greenhouse were very precise as these were automatically collected at a very high temporal resolution. The recordings, however, tell only a part of the story, as data on energy consumption of the computer control system, the reverse osmosis water treatment and the pumps are lacking.

Nutrients. As no information is known on theoretical nutrient requirements of crops, and since nutrient additions do not seem to follow a regular pattern, it is quite impossible to determine the reliability and completeness of the nutrient input dataset on sites where manual addition took place. Reliability depended on the consistency of the administration regarding manual addition of fertilizer as well as on the accuracy of the weighting. At the Boston sites these data could not be verified by the researchers.

At the QO hotel, however, a monitoring system recorded fertilizer application data. Hence, the synthetic nutrient supply data were considered to be very accurate. Also, data on organic fertilizer additions are regarded as reliable, as the farmer kept the empty containers for this research to verify. Fertilizer additions at the greenhouse were administered once the electrical conductivity (EC) dropped below a critical value. EC, however, doesn't differentiate between concentrations of different nutrients.

Financial considerations for data collection on resource use. Water and in particular, nutrients and energy, are costly resources. Surprisingly, the use of these resources is not precisely monitored, evaluated and controlled by the urban farmers. Two out of three farms under investigation were run without regular data collection on resource use. The third farm did collect a lot of data but seemingly did not apply it in its operation.

As this research project showed, even by installing small and simple monitoring equipment insights can be gained in the consumption of these resources during the production of crops, helping with efficient resource application which could result in producing crops at minimal costs. This project increased the awareness for these considerations, as was confirmed in our talks with the farmers.

Data on resource availability in urban waters

Both in Boston and in Amsterdam, rainfall data have been monitored by renowned institutes for a long time, supplying an extensive and reliable dataset to this study to execute rainwater availability computations. In both cities, however, sewage availability could only be determined using a wide range of generalized data and assumptions, making for a weak assessment. Placing equipment into local pipe segments to carry out flow measurements would be recommended to determine the available sewage quantity locally.

Moreover, no water quality data on sewage streams were available at a local scale. In both cities, concentrations of wastewater constituents

Table 3
Quality and availability of data for the three different case study sites.

	Resource demand			Resource supply		
	Water	**Energy**	**Fertilizer**	**Sewage quantity**	**Sewage quality**	**Rainwater quantity**
Boston						
Eastie Farm	Unknown	N/A	Unknown	Poor	Mediocre	Adequate
Corner Stalk Farm	Unfit	Adequate	Unknown	Poor	Unfit	Adequate
Amsterdam						
QO hotel	Mediocre	Mediocre	Adequate	Poor	Unfit	Adequate

were only collected at the centralized treatment station. Using water quality data at the end of a sewer system where flows from combined and separate sewers have been combined, underestimates the concentrations of compounds in sanitary waste pipelines of a separate sewer system. Taking wastewater quality samples from the sewer segment under investigation, and analysing its COD, ammonium, nitrate and (ortho-) phosphate content, would solve this problem.

Recommendations on future research on resource demand and availability

For prospective studies on urban farming it is recommended to incorporate scenario analysis. Both scenarios on the future availability and demand for resources need to be studied. Changes in spatial planning, urban development, demographics and trends in (water, energy, food and fertilizer) consumption and climate, can all influence the allocation of stocks and the dimension of flows, such as wastewater production and rainwater availability in the local WENF nexus. Expansion of urban farming activities could increase the demand for these resources.

Moreover, it is recommended to take a closer examination of the economics of resource reuse from urban waters in urban farms. Currently, resource recovery from sewage in western economies predominantly takes place at central wastewater treatment plants. Estévez et al. [8], however, showed that decentralized treatment is in line with the philosophy of a circular economy. Although significant amounts of resources could be harvested from local wastewater, it is questionable whether it is financially feasible to install small local treatment facilities to harvest energy and nutrients from sewage. Future studies should point out the breakeven point, indicating at which sewage volume resource savings (both publicly and commercially) surpass capital expenditures for a (local or extended central) treatment facility.

Conclusion

To investigate resource demand of three urban farms and to quantify the available water, energy and nutrients in urban waters surrounding these case study sites their actual on-site flows were studied using the Water Energy Nutrient Food nexus evaluation framework [14].

Three very different types of urban farming were studied. From these results a few conclusions can be drawn. First of all, a critical reflection teaches that not all data collected in this study have sufficient reliability to contribute to solid quantitative recommendations on the feasibility of creating a closed loop resource system through local food production. Acquisition of quality data turned out to be the biggest challenge in WE(N)F nexus research. The methods for on-site data collection and local case study analysis brought to the surface a wide range of data gaps. Substantial parts of resource flows and stocks of water, energy and nutrients are hardly or not at all monitored in practice. It is recommended for future research that water, nutrients and energy demand series are recorded during at least an entire growing period, whether that period lasts a year (like at container farm Corner Stalk) or from spring until fall (like at open field community farm Eastie Farm) to see the impact of seasons on resource use and to compute adequate storage requirements.

Nonetheless, it can be concluded that demands for water and nutrients (nitrogen & phosphorus) for a greenhouse in Amsterdam, a community farm and a container farm in East-Boston can be met by resources present in urban waters (rainwater and wastewater) in the direct vicinity. The container farm and the greenhouse could even provide sufficient water for their operation by solely capturing water falling on their own roofs. Whether enough energy is available to operate each of these farms, depends on the type of farming system. If highly mechanized, it may not be possible.

Indoor culture at Corner Stalk container farm using water pumping, artificial cooling and lighting, while not making use of natural sunlight and ventilation, results in substantial energy consumption. The local wastewater stream analysed in this study cannot provide sufficient energy to operate one – let alone four – container farm unit. The QO greenhouse consumed less energy, because no air conditioning is used and the potential for catching natural sunlight is utilized optimally. The energy content from biogas harvested from the sanitary wastewater stream of a semi-full QO hotel, however, can only accommodate a part (10%) of the average energy consumption of the rooftop greenhouse in summer.

Spatial measures have to be taken in order to facilitate urban agricultural initiatives to grow crops without requiring water, energy and nutrient inputs from outside the city. Rainwater harvesting infrastructure and storage capacity must be supplied. In order to ensure a sustainable daily nutrient and energy supply to urban farms, a local connection to the nearby wastewater sewer combined with affordable (de)centralized treatment could be created, which would honor wastewater as the valuable resource it is. A micro-economical study must point out for which decentrally treated volume exactly it becomes profitable for farmers to invest in a wastewater reuse installation on site. Currently, large-scale resource recovery operations at centralized treatment facilities are preferred. Struvite harvested at these facilities can be distributed to local urban farms, and (partially) close the waste-to-resource loop in that way. Biogas produced during anaerobic digestion of sewage sludge could serve as energy supply to the net for everyone to benefit.

By installing small and simple monitoring equipment, necessary insights can be gained into the consumption of water, energy and nutrients for the production of crops. Urban farming could become more cost-efficient by investing in these monitoring programs and evaluating their results. Using the resources that are locally available would make urban farming more sustainable, while this circularity could also partially address urban (waste)water challenges.

Data availability statement

Data collected during the study is presented in the appendices of this article.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nexus.2022.100078.

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