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FERTILE CITIES: NUTRIENT MANAGEMENT PRACTICES IN URBAN AGRICULTURE

Rosanne Wielemaker[a], Oene Oenema[b,c] , Grietje Zeeman[a,d], Jan Weijma[a,d,]*

[a] Sub-department of Environmental Technology, Wageningen University, Wageningen, The Netherlands
[b] Department of Soil Quality, Wageningen University, P.O. Box 47, 6700 AA Wageningen, The Netherlands
[c] Wageningen Environmental Research, P.O. Box 47 , 6700 AA Wageningen, The Netherlands
[d] LeAF, 6708 WG Wageningen, The Netherlands

* Corresponding author, P.O. box 17, 6700 AA Wageningen, jan.weijma@wur.nl

Abstract

Cities are increasingly targeted as centers for sustainable development and innovation of food systems. Urban agriculture (UA) is advocated by some as a multi-faceted approach to help achieve urban sustainability goals, as it provides possible social, economic and environmental benefits. The role of UA in restoring resource cycles receives increasing attention, especially with regard to assimilating urban waste. However, there is little information on how nutrients are managed in UA in industrialized countries. To examine nutrient management in UA, data was collected from a total of 25 ground-based UA initiatives in the Netherlands on i) preferences for types of fertilizers, and ii) quantity and quality of fertilizers used including nutrient composition and organic matter content. The main inputs at urban farms were compost and manure, high in organic matter content. The total nutrient inputs were compared to nutrient demand based on crop nutrient uptake in order to determine nutrient balances. Results show that mean nutrient inputs exceeded mean crop demand by roughly 450% for total nitrogen, 600% for phosphorus and 250% for potassium. Mean inputs for plant-available nitrogen were comparable to crop uptake values. The surpluses, particularly for phosphorus, are higher than fertilizer application limits used for conventional farming in The Netherlands. While nutrient input calculations were subject to several uncertainties, e.g., due to lack of accuracy of the data supplied by the farmers, results show a salient indication of over-fertilization and thus a suboptimal nutrient use. If UA continues to expand across cities these observed nutrient surpluses may pose a risk for local surface waters and groundwater as well as soil quality. The need to improve nutrient management in UA is evident. Soil tests, harvest logging and book keeping of nutrient inputs would improve data quality and may help balance nutrient inputs with nutrient outputs.

Keywords: urban farming, nitrogen, phosphorus, potassium, organic matter, fertilizer use

1. Introduction

The long-term sustainability of urban areas has increasingly been called into question due to their dependency on non-renewable resources (McDonnell and MacGregor-Fors, 2016, Rees and Wackernagel, 1996). In response, the concern about the role and contribution of cities to sustainable development has prompted research agendas that regard cities as places that concentrate opportunities for change (Revi and Rosenzweig, 2013, Voytenko et al., 2016, Wolfram and Frantzeskaki, 2016). The production of food in or around urban areas, generally known as urban agriculture (UA), has been proposed by many as an effective intervention to address various issues of urban sustainability (Ackerman et al., 2014, Deelstra and Girardet, 2000, Pearson et al., 2010, Smit et al., 1996, Specht et al., 2013). Especially the diversity in activities, scales, and purposes of UA offers ample opportunities to integrate UA in the built environment and to contribute to various sustainability goals. UA has been advocated to increase local food provisioning, reduce supply chains and transportation distances, increase urban green, reduce the urban heat island effect, increase urban water retention and infiltration, increase bio-diversity in cities, provide opportunities for employment, education and recreation, and foster community cohesion (Lorenz, 2015, Mok et al., 2014, Artmann and Sartison, 2018). UA has also been identified as an auspicious component in repairing biological resource cycles within the built environment (Deelstra and Girardet, 2000, Drechsel and Kunze, 2001, Smit and Nasr, 1992). As such, water, energy, and materials can be recycled between UA and other urban functions.

Cities currently import nutrients contained in food and materials and discharge these as solid waste and wastewater streams with only meager nutrient and organic matter (OM) recovery and reuse. By assimilating these nutrients as composts and bio-fertilizers, UA could reintroduce nutrients into the food system and contribute to restoring the nutrient cycle. The use of compost and animal manure is a widespread practice on urban farms (Metson and Bennett, 2015). These soil amendments, high in OM, positively enhance soil quality. Increased soil OM and soil porosity facilitate water infiltration and water retention, serving as buffers during heavy rainfall (Taylor and Lovell, 2014) and retain water longer during episodes of drought. Soils with a history of urban uses such as housing, industrial production, and disposal activities, are often nutrient-poor, compacted and low in organic carbon. These urban soils may benefit from added soil amendments and farming practices (Lorenz, 2015). Moreover, using urban compost as well as other urban organic waste streams, allows urban farms to facilitate nutrient cycling on a local scale (Dewaelheyns et al., 2013). Metson and Bennett (2015) have shown that 73% of inputs used in urban farms in Montreal, Canada originated from local sources including green waste compost, vermicompost, and locally-produced manure. Grard et al. (2015) demonstrated the value of using urban organic waste as a growing substrate on rooftop farms in France; results indicated high crop yields and low levels of heavy metals in the harvested crops compared to European norms (N^o 1881/2006). The use of nutrients recovered from human excreta in UA can also contribute to closing urban nutrient cycles as shown by Chrispim et al. (2017) and Wielemaker et al. (2018). Increased technology developments in this field provide opportunities for nutrient recovery and reuse in UA in the form of fertilizers or soil amendments.

Despite the potential benefits for improved urban soil quality and increased nutrient availability, intensive UA production systems and fertilization practices can also result in negative ecological effects, both locally and regionally (Lorenz, 2015, Safi, 2011, Taylor and Lovell, 2014). The eager use of fertilizers and the lack of careful management of nutrients by urban farmers can lead to surpluses of macronutrients, nitrogen (N), phosphorus (P) and potassium (K), (Huang et al., 2006, Metson and Bennett, 2015, Wielemaker et al., 2018, Witzling et al., 2011), as well as the accumulation of trace metals, such as cadmium and copper (Lorenz, 2015) (Hargreaves et al., 2008).

Urban farms often follow organic farming practices (with or without certification), which means that they are limited to using the types of fertilizers that are permissible in organic agriculture. Commonly organic amendments such as manure and composts are the main fertilizer source (Bergström et al., 2009). When these amendments are applied at a rate to meet the N requirement of crops, the amounts of P and K applied often exceed crop requirements (Eghball, 2002, Maltais-Landry et al., 2015, Maltais-Landry et al., 2016, Mikkelsen and Hartz, 2008). Witzling et al. (2011) found high nutrient levels in community gardens in Chicago, with P and K, and sometimes N levels exceeding soil fertility recommendations required for optimal crop growth. Similarly, Metson and Bennett (2015) found a surplus of 0.316 Gg P yr $^{-1}$ in surveyed urban farms in Montreal in 2012 (averaging to 1013 kg P ha^{-1} yr^{-1}). Another study on home gardens in Flanders, Belgium found 89% of vegetable gardens to fall under soil fertility class ‘high’ for soil P content (Dewaelheyns et al., 2013). The over-fertilization of P may result in the saturation of the soil P sorption capacity and increased P leaching and run-off, leading to environmental drawbacks such as eutrophication of surface waters (Schröder and Neeteson, 2008, Van Grinsven et al., 2016, Maltais-Landry et al., 2016). The build-up of any nutrient in soils to beyond recommended levels is an inefficient use of resources; it decreases nutrient use efficiency and can result in soil-nutrient imbalances and/or unfavorable pH levels (Mikkelsen and Hartz, 2008, Tian and Niu, 2015).

In recent decades UA has been gaining ground in various forms such as allotment gardens, community gardens, harvest farms and commercial farms, across open spaces, rooftops, greenhouses, and as indoor farms (Lorenz, 2015, Thomaier et al., 2015). This trend is also visible in the Netherlands. There is, however, little information on how nutrients are managed on urban farms, which kinds and amounts of fertilizer inputs are used, their origin, and how current practices relate to the current regulatory frameworks for nutrient management in agriculture (i.e., Manure and Fertilizers Act). Research on nutrient budgeting has extensively been conducted in developing countries, such as Vietnam, China, Afghanistan, and several African countries (e.g., Abdulkadir et al., 2013, Huang et al., 2006, Khai et al., 2007, Safi, 2011, Wang et al., 2008). Previous studies on UA in industrialized countries primarily highlight the economic and social facets of UA (e.g., Duchemin et al., 2008, Smit et al., 1996, Specht et al., 2015, Thomaier et al., 2015, Zasada, 2011), and only few studies focus on nutrient management (e.g., Dewaelheyns et al., 2013, Grard et al., 2015, Metson and Bennett, 2015, Wielemaker et al., 2018). If UA is to play a role in the closing of urban nutrient cycles, as is advocated by many (Goldstein et al., 2016, LeGrand et al., 2014, Grard et al., 2015), it is important to first quantify the current fertilizer use in UA and evaluate the contribution of UA to nutrient recycling.

The overall objective of this study was to evaluate nutrient use in UA farms in the Netherlands, a densely populated and industrialized country increasingly implementing UA. While stimulating UA has benefits across social, economic, and environmental facets, careful consideration of the accumulative effects of farm practices needs to be understood. We conducted interviews with ground-based UA farms (sizes between 0.1-1.7 ha) across cities to collect information on farmer preference for the type of nutrient inputs (fertilizers, manures, composts, soil amendments). We quantified N, P, and K (NPK) inputs, the three primary macronutrients, at farm level. In addition, OM inputs were also quantified, as soil OM is broadly recognized as an important aspect of soil quality and fertility (Hijbeek et al., 2017). The calculations allowed us to evaluate fertilization practices and identify over or under fertilization for NPK compared to crop nutrient uptake as well as compared to legal application limits for N and P.

2. Methods

2.1. Selection of UA Initiatives, Interviews and Data Collection

The definition of UA used in this research is: the production of food in and around cities for the purpose of feeding local populations. Starting with an initial inventory (compiled via an internet search, word of mouth, and snowball sampling) of UA initiatives (n=60) located across various cities, a final selection of 25 urban farms was included in this study, using the following criteria: (i) willingness to participate, and (ii) ability to provide quantitative data. Only ground-based urban farms were included in this study, which are the dominant type of urban farming in the Netherlands.

Interviews were conducted in person and onsite, or via telephone, with the head farmer or a farm volunteer between May 2017 - March 2018 using a semi-structured questionnaire (see Supplemental Information). Onsite surveying was preferred as it allowed for additional data collection through observation (e.g. cultivated area, management, maintenance of composting facilities, crop types) (Cohen and Crabtree, 2006). The semi-structured interviews were advantageous for both interviewer and interviewee as they intended to be conversational and allowed for flexibility to enquire for details when needed. Most interviews conducted in person were voice-recorded (with consent from the interviewees) and later transcribed to distill data for data processing; interviews conducted via telephone were not voice-recorded. To clarify or verify collected information, the interviews were followed-up with questions via email or telephone.

Data collected during the interviews, both qualitative data on farmer practices and preferences, and quantitative data on nutrient inputs, were processed per farm separately, as well as compounded into data spreadsheets to facilitate comparison. Nutrient contents of manure, compost, and organic fertilizers were derived from the labels of bags or from literature (see Supplemental Information). Occasionally farmers were able to present results of chemical analyses of the manures or composts applied on their farms; when available, we used these values. An overview of the data collected, data sources and assumptions (when input-specific information was not available), and of the specifications used to make nutrient input calculations is provided in the Supplemental Information.

2.2. Data Processing and Analysis

Total inputs for OM and NPK were calculated, and for comparison across farms, inputs were expressed as kg ha^{-1} yr^{-1}. Inputs of NPK were compared with the uptake of NPK by crops commonly grown by UA initiatives. Reference values were used, and not an account of what was actually grown on each farm, because farmers could not supply detailed information on crops planted and respective harvests. Inputs were also compared to the legal application limits (2017) for N and P according to the Manure and Fertilizers Act (Meststoffenwet, 1986).

To assess the adequacy of soil OM inputs, these were expressed in terms of effective organic matter (EOM). EOM in manure, composts, and other organic fertilizers is defined as the fraction of OM that remains in the soil one year after its application to the soil (de Haan and van Geel, 2013). The amount of EOM inputs (kg yr^{-1}) at each farm was calculated using Equation 1, where HC stands for the humification coefficient (%), as reported by de Haan and van Geel (2013).

$$\text{EOM} = \text{HC} * \text{OM} \qquad \text{Equation 1}$$

Since plants acquire N from the soil only in plant-available forms, total N inputs (kg yr^{-1}) per farm were also expressed in terms of plant-available nitrogen (PAN) inputs (kg yr^{-1}). PAN indicates the fraction of the total N (N_{tot}) input (kg yr^{-1}) that is available to the plants during the first year after application. It also accounts for the N that is vulnerable to losses via leaching, denitrification, and (when in ammonium form) volatilization. The amounts of PAN were estimated for each fertilizer, using Equation 2 and fertilizer N equivalency (CN_{tot}), expressed as percentage coefficients (%). Fertilizer N equivalencies for composts, manures, and wastes are usually below 100%, because the organically bound N has to be mineralized first to ammonium-N forms (van Dijk et al., 2005). We assumed that all P from composts, manures, and wastes becomes available at similar rates as synthetic P fertilizers on the longer term, and hence the fertilizer P equivalency for the P inputs was set at 100%. Further, we assumed that all K is available and hence the fertilizer K equivalency was also set at 100% for all fertilizers and soil amendments (de Haan and van Geel, 2013).

$$\text{Plant available N (PAN)} = CN_{tot} * N_{tot} \qquad \text{Equation 2}$$

The total nutrient inputs were then compared to nutrient demand based on crop nutrient uptake to determine nutrient balances NPK uptake by crops, and thus withdrawal in harvested biomass, (kg ha^{-1} yr^{-1}) were retrieved from two literature sources: Bosch and De Jonge (1989) and Fink et al. (1999).

The Manure and Fertilizers Act of The Netherlands regulates N and P inputs to agricultural land via manure, and N and P application limits (*'gebruiksnormen'*) (van Grinsven and Bleeker, 2016). Manure application limits are expressed in total N and are 170 kg ha^{-1} yr^{-1} for arable land, and 170 to 250 kg ha^{-1} yr^{-1} for grassland, depending on a farm-specific permit (derogation). Application limits for N (expressed in PAN) indicate the annual allowance of N per hectare per crop and soil type, and may vary with crop yield (RVO, 2017b). Legal fertilizer N equivalencies ("*werkingscoëfficiënt*") apply when calculating N application limits (RVO, 2014). Application limits for P indicate the annual allowance of P per hectare and varies relative to soil P content. In this study, the N and P application limits for 2017 were used for comparison. While commonly no fertilizer P equivalency (CP (%)) is used for P inputs (kg yr^{-1}), the Manure and Fertilizers Act acknowledges that approximately half of the P in composts is soil-bound P and therefore uses a fertilizer P equivalency (CP) of 50% for composts (RVO), calculated using Equation 3. All other fertilizers and soil amendments were counted with a 100% equivalent. There are no application limits for K in the Manure and Fertilizers Act.

$$\text{Available P (compost)} = \text{CP} * \text{P} \qquad \text{Equation 3}$$

4. Results and Discussion

4.1. Characterization of the selected urban farms

A total of 25 UA initiatives (Table 1) were interviewed in several cities across the Netherlands (Figure 1): Amsterdam (5), Apeldoorn (1), Culemborg (1), Dordrecht (3), Groningen (1), Haren (1), Leiden (1), Maastricht (1), Middelburg (1), Rotterdam (5), 's-Hertogenbosch (1), Utrecht (1), Veenhuizen (1), and Wageningen (3). The majority of the farms were established after 2005 with over half established after 2012. Only a handful of farms (n=5) were over 1 ha in size, with 73% smaller than 0.5 ha. All farms showed ties to the local community and farmers emphasized the social benefits of their initiatives, including education, awareness raising, community building, and support for low-income and vulnerable groups. Meanwhile, over half of the farms had a commercial objective. The produce from these farms supplied own or local restaurants, were sold through membership shares (CSA), or were sold on-site or at local markets.

With the exception of two farms, the initiatives can be classified as ground-based-non-conditioned (GB-NC). Goldstein et al. (2016) defines this typology as: occurring directly on the ground (as opposed to in or on a building) and connected to the ambient environment (in contrast to e.g., greenhouses). The other two farms can be classified as ground-based-conditioned, growing in raised beds within a frame (contained soil). A few of the farms also managed one or more smaller hoop-house(s) or greenhouse(s) for season extension. For a more detailed account of the farms, and an overview of the interview data can be found in the Supplemental Information.

In total 77% of the interviewees were satisfied with the crop yields. Almost a quarter were less content, which they related to poor yields, lack of labor force, lack of mechanization, or poor soil quality. All farmers listed measures to further improve harvests, including crop rotation and planning, pest, disease and weed management, and nutrient and soil pH management. The majority of the farmers considered their farming practices to be sustainable for a host of reasons. Many alluded to their organic or ecological farming practices referring to the use of organic manure, biological-control of pests, the absence of pesticide use and the use of a crop rotation plan. Onsite composting, waste management and recycling, rainwater harvest and reuse, green energy use and reducing transport and packaging of products were reasons given to support their sustainability claims. Many farmers also considered their role in raising awareness amongst the community as one of their main contributions to sustainability.

All farmers also considered their resource management to be sustainable. The use of local, renewable, and/or organic sources of fertilizers as opposed to chemical fertilizers was the main reason provided. 35% of the farmers mentioned their onsite composting efforts as indication of their sustainable resource management. A meagre three of the farms considered their resource management to be less optimal because of the use of external inputs and uncertainty regarding the soil nutrient balance. To improve nutrient management many farmers indicated that a soil analysis would be appropriate, as well as (improved) onsite composting.

The preferences for fertilizers varied between farms. None of the farmers preferred synthetic fertilizers but rather preferred certified organic fertilizers derived from plant and animal residues, and sourced as locally as possible. However, in practice, farmers did not always/only use certified organic fertilizers, nor fertilizers sourced locally. Manure inputs at some farms were sourced onsite (i.e. from own farm animals), some were sourced directly from nearby (petting) farms, some from farms outside of the city, and others purchased packaged manure from retailers. Some farmers were adamantly against the use of fertilizers made from animal waste such as bone and blood meal, and sources of manure that could contain traces of antibiotics (administered to the animals). Most farmers conveyed that their fertilizer use practices were based on a mix of experience (62%), feeling (42%), knowledge (54%), and trial-and-error (50%); a minority indicated that advice found in literature (23%), on the packaging (15), or from experts (27%) and legislation (23%) guided their fertilizer use.

4.2. Fertilizer, organic matter and nutrient inputs

Table 1 shows which types of fertilizer inputs were used. While some inputs were produced onsite (e.g. farm-made composts and manure from own farm animals), all farms used at least one fertilizer input from external sources (produced off-site). Compost (used at 80% of the farms), manure (60%), and/or some other organic soil amendment (24%) were the main inputs. Supplemental macronutrient (40%), micronutrient (20%) and potassium fertilizers (16%) were also used at some farms. Calcium-rich soil amendments were also used (24%), primarily to modify soil pH. The variation in types and amounts of fertilizers used by farmers is reflected by the variation in the total nutrient and organic matter inputs calculated for each farm (Table 1).

4.2.1. Organic Matter

The calculations for farm inputs show a partiality for fertilizers rich in OM; particularly compost and manure contributed to OM loads with total OM inputs ranging between 700 and 138,100 kg OM ha^{-1} yr^{-1} (Table 1 and Figure 2). Whether the application of organic inputs increases soil OM depends on the current amount of organic matter in the soil, the type of organic input applied, crop type, and crop residue management, as well as temperature, humidity, soil texture, and soil cultivation (Hijbeek et al., 2017). As found by Loveland and Webb (2003), it is difficult to establish a critical level for soil organic matter for temperate regions. A steady soil OM input-output balance requires a total annual supply of EOM that is equal to the amount of soil OM that is degraded annually. Degradation of soil organic matter depends on soil characteristics such as soil type, soil pH, soil moisture, and temperature and C/N ratio, as well as on the level of soil cultivation. The rate of degradation of soil organic matter may vary between 1-5% per year. For agricultural land in The Netherlands, it has been estimated at the average degradation is 2000 kg OM ha^{-1} yr^{-1} (de Haan and van Geel, 2013). Therefore, to replenish soil OM degradation, an average input of 2000 kg EOM ha^{-1} yr^{-1} is recommended {de Haan, 2013 #38}. We observed that the average EOM input was much larger than the recommended EOM input; 84% of the farms (n=22) applied more than 2000 kg EOM ha^{-1} yr^{-1} and 76% (n=18) of the farms applied more than 5000 kg EOM ha^{-1} yr^{-1}. This indicates that most UA farms increase soil OM content.

4.2.2. Nitrogen, Phosphorus and Potassium

NPK inputs differed greatly between farms (Table 1 and Figure 2). Means ± standard deviations indicate the wide range of inputs across the 25 UA initiatives. For NPK these values were 789 ± 955 kg N ha^{-1} yr^{-1} , 168 ± 198 kg P ha^{-1} yr^{-1}, and 625 ± 698 kg K ha^{-1} yr^{-1}. The variations in inputs for UA farms smaller than 0.3 ha (n=15) were especially large, and on average higher compared to the inputs for UA farms larger than 0.3 ha (n=11) (Figure 3a). The UA farms with the highest nutrient applications were also amongst the smaller farms. Another relationship was found between the year in which the urban farm was established and the nutrient input. Older farms (n=9), established before 2010, displayed lower nutrient applications (average P application of 45 kg ha^{-1} yr^{-1}) than younger farms (n= 16) (average P application 237 kg ha^{-1} yr^{-1}) (Figure 3b). The highest nutrient applications where on farms with clay soils (Figure 3c). See Supplemental Information for a detailed account of the nutrient loads per UA initiative.

4.2.3. Comparison of NPK inputs with NPK withdrawal in harvested crops

Partial NPK input-output balances of UA farms provide an indication of the NPK surpluses or deficits, the potential NPK accumulation in the soil, as well as of the vulnerability of these UA farms for NPK losses to the wider environment. Mean total N inputs (789 ± 955 kg ha^{-1} yr^{-1}) were 4 to 5 fold larger than the estimated N withdrawal via harvested crops (Figure 4a); N withdrawal averaged to 161 ± 76 kg ha^{-1} yr^{-1} and 203 ± 88 kg ha^{-1} yr^{-1}, calculated from data extracted from two literature sources respectively (see supplemental information). Independent-sample t-tests (confidence interval percentage 95%) were conducted to compare the difference in means between N inputs and the withdrawal values. There was a significant difference in means (two tailed) for total N inputs and N withdrawal values found in Bosch and De Jonge (1989) ($p = 0.003$) and Fink et al. (1999) ($p = 0.005$). Mean PAN inputs were only 191 ± 192 kg ha^{-1} yr^{-1}, which fall within the range for the N withdrawal estimates; the difference in means between PAN inputs and N withdrawal values found in Bosch and De Jonge (1989) ($p = 0.480$) and Fink et al. (1999) ($p = 0.779$) was not significantly different. The large difference between total N input and PAN input is due to the low fertilizer N equivalencies (CN_{tot}) for composts, manures, and wastes. These fertilizers release only a small fraction of total N in plant-available forms in the year of application. However, the residual release of PAN during subsequent years is relatively high, and PAN may accumulate in the soil with continued use of these fertilizers at high rates. UA farmers do seem to account for residual effects, as the total N input clearly decreased with the age of the farm (Figure 3b).

Mean P inputs (168 ± 198 kg ha^{-1} yr^{-1}) were much higher than, and significantly different from, estimated P withdrawal via harvested crops (24 ± 12 kg ha^{-1} yr^{-1} (p =0.001) and 32 ± 13 kg ha^{-1} yr^{-1} (p =0.002), for the two literature sources respectively) (Figure 4b). P inputs for 44% of the farms were below the maximum value of P withdrawal (brussel sprouts ~ 60 kg P ha^{-1} yr^{-1}), the remaining 56% of P inputs surpassed this maximum value. Mean K inputs (625 ± 698 kg ha^{-1} yr^{-1}) were also much higher than estimated K withdrawal via harvested crops (226 ± 104 kg ha^{-1} yr^{-1} (p =0.009) and 372 ± 102 kg ha^{-1} yr^{-1} (p =0.020), for the two literature sources respectively). A total of 36% of the farms had K inputs that exceeded even the highest value for K output via harvested crops (red beet ~ 460 kg ha^{-1} yr^{-1}) (Figure 4c).

The fertilization adequacy can further be evaluated on the basis of N:P:K mass ratios. Figure 5 shows the position of various common vegetable crops in the triangle based on their NPK contents and normalized to percentages (only selected crops are shown in Figure 5; see Supplemental Information for full list). The mean NPK inputs of the 25 UA farms are also plotted in the triangle. The mean NPK mass ratios of crops at harvest average 40:6:54 (calculated for both Bosch and De Jonge (1989) and Fink et al. (1999)). However, there is a significant variation between crops, for example for radish it is 53:4:43 and for endive 34:4:62). Ratios for the NPK inputs are also shown with PAN (PAN:P:K). The ratios of NPK inputs based on total N (average= 49:10:41) compare more closely to crop uptake ratios than NPK input ratios based on PAN (average= 21:16:63), indicating excess input of P and K relative to available N. Ratios of NPK inputs across farms are fairly similar with the exception of one farm (UA 15). UA 15 had only input of vermicompost, which has low N:P and N:K ratios.

The 25 urban farms show relatively large mean NPK surpluses and a mismatch between inputs and demands in terms of NPK ratios, both indicating that current nutrient management practices on urban farms are not optimal. The preference among UA farms for manure and compost often leads to high P and K loads that exceed plant requirements (Maltais-Landry et al., 2016). While the nutrient surplus exhibited by some of the urban farms do not by default indicate total nutrient losses to the environment directly, they can be used as an integrated measure of nutrient loss potential (Öborn et al., 2003). The surplus may be stored within the system and may be lost to the environment; its dissipation into the environment depends on various factors including rainfall, soil type, and slope, soil tillage, crop type, and application method (Edwards and Withers, 1998, Lord et al., 1999). While some oversupply of P and K might be acceptable in single years, since they can be stored in the soil to a larger extent than N, the long term balance would need to indicate ratios similar to those required by crops plus some unavoidable losses (Winker et al., 2009). Two options for improving the nutrient balance include: 1) increasing P export by cultivating plants with high plant P concentrations (e.g., grain, potato and cabbage crops) and 2) adjusting fertilizer inputs to better match crop uptake requirements (Maltais-Landry et al., 2016). Reducing over-fertilization of especially P, by simply reducing application rates of composts and manure would result in N under-fertilization, leading to lower crop yields and crop N deficiency (Maltais-Landry et al., 2016, Berry et al., 2002). Shifts in N:P:K ratios are needed. Instead of relying completely on composts and manures, with a constrained N:P stoichiometry, these organic amendments should be replaced by fertilizers with a high N:P ratio and/or decoupled nutrients (Maltais-Landry et al., 2016).

4.2.4. Comparison of N and P inputs with legal N and P application limits

Nutrient management practices in the Netherlands have long been discussed and criticized because of the high N and P surpluses in Dutch soils (Schröder and Neeteson, 2008, Van Grinsven et al., 2016). The implementation of a series of governmental regulations in the late 1990’s (especially in response to the 1991 Nitrate Directive (91/676/EEC)) have halved the mean N surplus from 250 kg ha^{-1} in the mid-1990s, and have led to a strong decrease in mean P surpluses since the early 1990s, approaching zero kg ha^{-1} (Van Grinsven et al., 2016). However, while conventional agriculture in the Netherlands has to comply with strict regulations for fertilization according to the Manure and Fertilizers Act, UA falls somewhere between existing categories. Due of their small size (<3 ha), and low number of animals (whose manure amounts to <350 kg N yr^{-1}), these farms have an exemption from the compulsory N and P application limits and from nutrient management administration obligations, according to Article 43 of the Implementing Arrangement (Uitvoeringsregeling) of the Manure and Fertilizers Act (Meststoffenwet, 1986).

Further, of the included farms, 10 fall under the land use category for ‘agricultural land’; the other farms fall under the following categories: ‘recreation’ (5), ‘built’ (4), ‘semi-built’ (3), and ‘industrial’ (3) (Kadaster, 2012). If classified as agricultural land, UA would have to adhere to the same regulations as conventional agriculture, with the maximum application rates for agricultural (grass land and arable land) of 35 kg P ha^{-1} yr^{-1} and 170 kg N ha^{-1} yr^{-1} (article 2.4.b). However, if classified as “other land” the maximum phosphorus application derived from animal manure, compost, recovered phosphorus fertilizers and organic fertilizers made form plant-derived materials (article 2.4.a, Dutch Manure and Fertilizer Act) amounts to 20 kg P_2O_5 ha^{-1} yr^{-1}. For other land, a one-time dosage of vegetative compost of 200 ton dry matter ha^{-1} is also permitted (article 2a.1).

Total N and P inputs for all 25 farms were compared to the legal application limits (2017) for N and P (see Table 2). The N (as PAN) inputs were on average higher than the mean N application limits but lower than the highest N application limit (for white cabbage = 320 kg N ha^{-1} yr^{-1}). Considering that the application standards for N are given in ha^{-1} yr^{-1} per crop, if two or more crops are planted in succession in one year, the application limit is increased to the sum of the individual limits per crop. Total P inputs are much higher than the P application limits for agricultural land. Total P inputs exceeded the lowest P application limit (22 kg ha^{-1} yr^{-1}) on 84% of the farms and 72% of the farms exceeded the highest P application limit (33 ha^{-1} yr^{-1}). The majority of farms that indicated to comply to legal application limits, largely over applied P. Using a fertilizer P equivalence for compost inputs shifted only one farm from a position of over-application of P to falling within the regulatory limits.

The Manure and Fertilizers Act was implemented to reduce N and P pollution of surface waters and groundwater by agricultural practices. However, small urban farms have an exemption from the compulsory N and P application limits and from nutrient management administration obligations because these farms have less than 3 ha of agricultural land and/or produce in total less than 350 kg of manure N per year on the farm. Because of this exemption, there is also no control and verification. Currently, the number of UA farms is relatively low, and they have a relatively small cultivated area. However, if current nutrient management practices on UA farms persist over long periods, and/or if the number of UA initiatives continues to grow and if new initiatives adopt similar practices, then these practices do raise concern from an environmental perspective. A further increase of the cultivated area will increase the environmental risks. Run-off from urban farms can either enter surface waters, leading to algal blooms, or, for cities with a combined sewer, wastewater treatment plants will have to manage increased nutrient loads from run-off. Equally of concern, the high compost and manure application rates may lead to accumulation of heavy metals in soils, and in vegetables. Heavy metal loads and organic micro pollutants through land application of fertilizers and soil amendments are also regulated by the Manure and Fertilizers Act; approved composts and soil amendments have to comply with heavy metal and micro pollutant concentration limits, and then may be increasingly applied until a maximum application per hectare of 100 kg N, 35 kg P, 150 kg K, or 3000 kg OM is reached ((RVO, 2017a, RVO, 2017c)). The lack of data on heavy metals and micro pollutant concentrations of the inputs used on UA farms makes it difficult to assess whether concentration limits are exceeded. Regardless, considering that many farms exceed the indicated application limits, most interviewed farms may breach the heavy metal and micro pollutant legislation.

4.3. Data Uncertainties

Several uncertainties affected the accuracy to calculate farm-level nutrient inputs, especially given the high-demand for data for this research: 1) the (lack of) accuracy and comprehensiveness of the data supplied by the farmers; 2) the estimates on the nutrient composition of manures and composts; 3) the lack of information on past fertilization regimes and soil nutrient stocks; 4) the lack of information of farm management (e.g. tillage practices, fertilizer placement and timing). Despite these limitations, we consider the quality of the partial nutrient balances sufficiently robust to assess the nutrient management practices of UA farms, which was our main goal. For instance, assuming a magnitude of possible error for N content in manure of 30% (as used by Mulier et al. (2003) in a similar study), to account for variability in nutrient composition estimates, does not change the main findings of this study (mean PAN inputs only change by ±3%). Likewise, the inclusion of past fertilization regimes and the mineralization of organic N from previous fertilizer applications, would only magnify the surpluses already observed. While P from previous applications accumulates in the soil, organic nitrogen is further released as PAN; a yearly application of chicken/pig or cow manure, for example, increases the fertilizer N equivalence by 20 and 35% respectively (de Haan and van Geel, 2013).

The initial intention to conduct full farm-gate balances was discarded early on as collecting data on fertilizers used and the respective amounts applied was challenging enough and farmers could not supply detailed information on crop harvests (kg yr^{-1}) and succession planting. Planting multiple crops in succession throughout a year changes the amount of crop nutrient withdrawal, which could not be accounted for in this study. However a quick analysis considering two crop plantings in a year for comparison returned the following conclusions, which echo the conclusions already presented: 1) The majority of the farms risk under fertilization of PAN, 2) The mean P and K inputs for the UA farms would still exceed P and K crop withdrawal. Especially for P, the difference in means between inputs and crop withdrawal, considering two plantings, remains significantly different compared to the two literature sources: Bosch and De Jonge (1989) (p =0.006) and Fink et al. (1999) (p =0.016).

Furthermore, most farmers had not recorded which fertilizers they had used that year and many could provide only rough estimates of the amounts applied, let alone the exact placement and timing of the fertilizer application, and crop residue, mulching, and soil cultivation practices. Detailed farm nutrient balances would however benefit farmers in targeting and improving their nutrient management practices. Periodic soil testing and book keeping of all fertilizer inputs as well as yield and harvest logging, would make it possible to calculate input-output balances at farm resolution. Farm specific data on yield would have allowed for further analyses between fertilizer inputs and respective yield success. To achieve even more complete farm nutrient balances, N deposition, N fixation, and nutrient sedimentation could be included.

5. Conclusions and Outlook

NPK inputs varied greatly among the 25 UA farms studied. Mean total NPK inputs were much larger than NPK output via harvested crops. There was a considerable range in fertilizer types, with a clear preference for composts and animal manures rich in OM. However, most OM-rich inputs are also the culprit of the excess fertilization due to the small faction of total N inputs that is plant-available and their constrained N:P:K stoichiometry. While, mean input of PAN was roughly similar to the mean N withdrawal via crop uptake, the P and K inputs largely exceeded their withdrawal via harvested crops. The persistence of current nutrient management practices on urban farms over long periods, and/or the adoption of similar practices at new urban farms increases the risks of inefficient nutrient management and excessive nutrient losses. While this research is unable to determine whether the excess NPK inputs have accumulated in the soil or are lost to the environment, the excesses do call to attention the need for increasing nutrient use efficiency and merits further examination. Just as conventional agriculture in the Netherlands has to comply with N and P application limits, UA initiatives might require similar attention. Longer term monitoring of nutrient inputs, outputs and soil nutrient pools will better help determine which targeted measures and tools could assist farmers in improving nutrient use efficiency and better inform whether measures are needed to regulate fertilizer use in UA.

The broader perspective of this study was to examine whether the nutrient demand of UA could be used to assess how much NPK from urban waste streams could be absorbed by UA, so as to achieve effective nutrient recycling within urban boundaries. Currently it is difficult to quantify how much NPK can be assimilated by UA, based on current UA practices, due to the huge diversity in UA practices and limited amounts of quantitative data. Only with a stark decrease in nutrient inputs could actual UA fertilization practices be taken as a point of departure to determine the extent to which UA may assimilate nutrients from urban waste streams to repair nutrient cycles within the built environment. However, in cities saturated with nutrients in solid waste and wastewater, it seems unsuited to perpetuate the current nutrient management practices of UA farms, including importing manure from rural areas to UA. Because UA is inherently urban and thus is in proximity to nutrient sources in waste, UA lends itself for establishing local nutrient cycles, especially for nutrients in forms too costly to export back to other agricultural areas (i.e. voluminous and heavy).

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Table 1 Participating urban agriculture initiatives with general farm characteristics, fertilizer use, and nutrient and organic matter inputs

UA study reference num.	GENERAL INFORMATION	Commercial[1]	Social[2]	year established	soil type	Cultivated Area[3]	Land use type[4]	FERTILIZER INPUTS	manure	compost	soil amendment	mulching	Macronutrient fertilizer	K fertilizer	Micronutrient fertilizer	Calcium (chalk)	NPK & OM INPUTS	Organic Matter (OM)	Effective Organic Matter (EOM)	Nitrogen (N)	Plant-Available Nitrogen (PAN)	Phosphorus (P)	Potassium (K)
#				yr		ha	Kadaster		◦ = input at the UA initiative									$ha^{-1}yr^{-1}$					
1		●		2012	Sand/Loam	1.00	Industrial Area		◦	◦								3691	2798	104	25	24	71
2			●	2015	Clay	0.07	Recreation		◦	◦						◦		55951	41150	1693	329	350	1273
3		●	●	2004	Clay/Sand	1.12	Agriculture		◦									8294	5805	289	87	67	276
4		●		1995	Clay	0.12	Recreation			◦	◦		◦	◦				10764	7525	408	120	61	357
5		●		2007	Clay	0.20	Built			◦	◦		◦	◦				12411	8622	505	223	89	429
6			●	2015	Sand	0.20	Recreation		◦	◦		◦	◦	◦	◦			15610	10158	777	264	204	664
7		●		1960	Peeted	1.60	Agriculture				◦		◦					1406	703	133	66	17	104
8		●		2017	Clay	0.25	Semi-Built		◦	◦			◦		◦			71390	52510	2167	455	433	1668
9		●		2017	Clay	0.08	Semi-Built		◦	◦	◦		◦		◦	◦		138159	103503	3925	633	748	2736
10		●		2014	Sand/Clay	0.38	Agriculture				◦		◦			◦		738	369	103	52	19	147
11			●	2014	Potting soil	0.10	Semi-Built			◦	◦				◦	◦		9608	30183	291	116	57	204
12			●	1996	Sand/Clay	0.15	Agriculture		◦	◦								2813	1407	101	41	26	111
13			●	2012	Sand/Loam	0.28	Agriculture		◦	◦						◦		24843	17774	1119	575	251	1061
14		●	●	2006	Sand/Clay	1.86	Agriculture			◦								12875	10871	268	34	57	193
15			●	2012	Sand	0.23	Industrial Area			◦								15017	11263	371	37	78	64
16		●		2015	Clay	0.25	Built		◦	◦								29008	19516	818	161	174	767
17		●	●	2007	Sand	1.71	Agriculture		◦	◦				◦				3926	2424	131	42	32	228
18			●	2011	Sand	0.02	Built		◦			◦			◦	◦		13125	11812	219	87	53	187
19			●	2012	Sand	0.08	Recreation		◦	◦								21372	14473	1064	250	261	856
20		●	●	2005	Sand	0.53	Agriculture			◦			◦					2356	1767	109	23	19	82
21		●	●	2005	Sand	0.49	Agriculture		◦	◦			◦					5348	3855	204	52	42	175
22			●	2014	Sand/Clay	0.61	Agriculture		◦				◦					9348	6534	291	97	49	373
23			●	2014	Clay	0.50	Semi-Built			◦								9308	6981	260	39	50	181
24			●	2011	Clay	0.11	Recreation		◦	◦		◦						39154	24719	1920	577	513	1631
25			●	2014	Clay	0.14	Industrial Area			◦		◦						51166	38375	2454	368	521	1788
								#	15	20	6	4	10	4	5	6	avg.	22707	17404	789	190	168	625
								%	60	80	24	16	40	16	20	24	s.d.	30261	22611	955	193	198	698

[1] A commercial farm is primarily focused on generating income, usually through the sale of the produce

[2] A social farm is primarily focused on providing social activities, such as education, community building, awareness creation, day care for vulnerable groups.

[3] The area cultivated with vegetables, which excludes additional area used for e.g. animal husbandry, fruit trees, social spaces.

[4] Land use as indicated by latest available document from the Central Agency for Statistics (CBS) on Land Use (Kadaster, 2012)

Table 2. Comparison of mean nutrient inputs at urban farms (this study) to legal nitrogen (N) and phosphorus (P) application limits for conventional farming according to the Dutch Manure & Fertilizers Act

	Nitrogen							Phosphorus				
	N Input at UA farms		N Application Limits (Soil Type)					P Input at UA farms[1]		P Application Limits (Soil P content)		
	Total N	PAN	Clay	Sand-NWC	Sand-S	Loam	Peat	P_2O_5	P	Low	Medium	High
	$kg\ ha^{-1}yr^{-1}$		$kg\ N\ ha^{-1}yr^{-1}\ crop^{-1}$					$kg\ ha^{-1}yr^{-1}$		$kg\ P_2O_5\ ha^{-1}yr^{-1}$		
Mean	789	197	209	187	152	152	194	267	116	75	60	50
s.d.	955	189	66	59	45	45	63	272	119	-	-	-

[1] The Manure and Fertilizers Act uses a fertilizer P equivalency (CP) of 50% for composts. For comparison to P application limits, this equivalency was used when applicable to composts to calculate UA farm inputs.

Figure 1. Map of the 25 interviewed urban agriculture initiatives across cities in the Netherlands

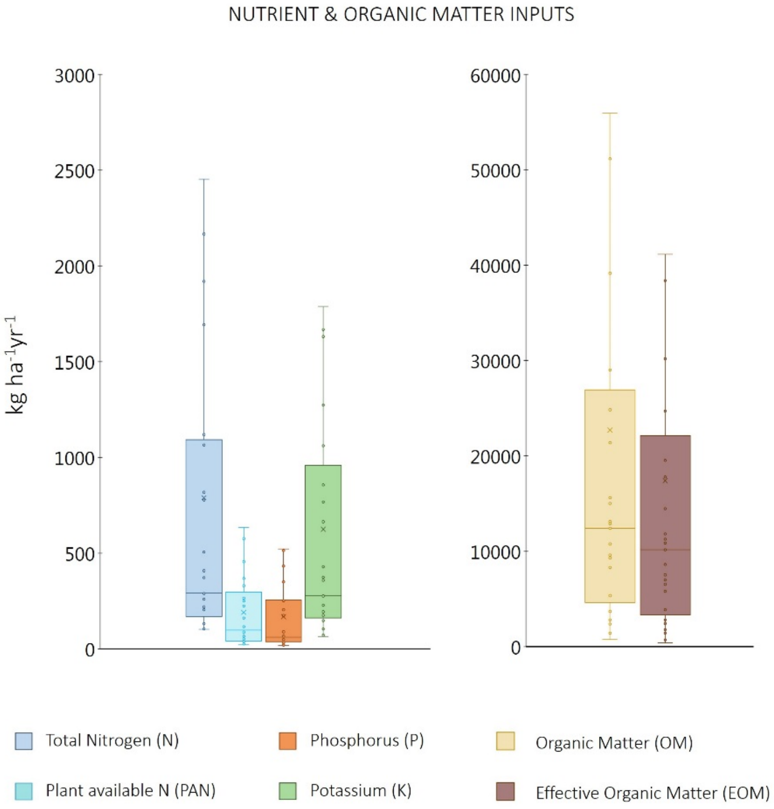

Figure 2. Box plots of organic matter (OM) and effective organic matter (EOM) inputs (a) and nitrogen (N), plant-available nitrogen (PAN), phosphorus (P) and potassium (K) inputs (b) for all UA initiatives. Boxes show the interquartile range (25 to 75% values). The line in the boxes shows the median value and the 'x' shows the mean value. Whiskers indicate the total range of the values, outliers (>1.5 interquartile range) excluded.

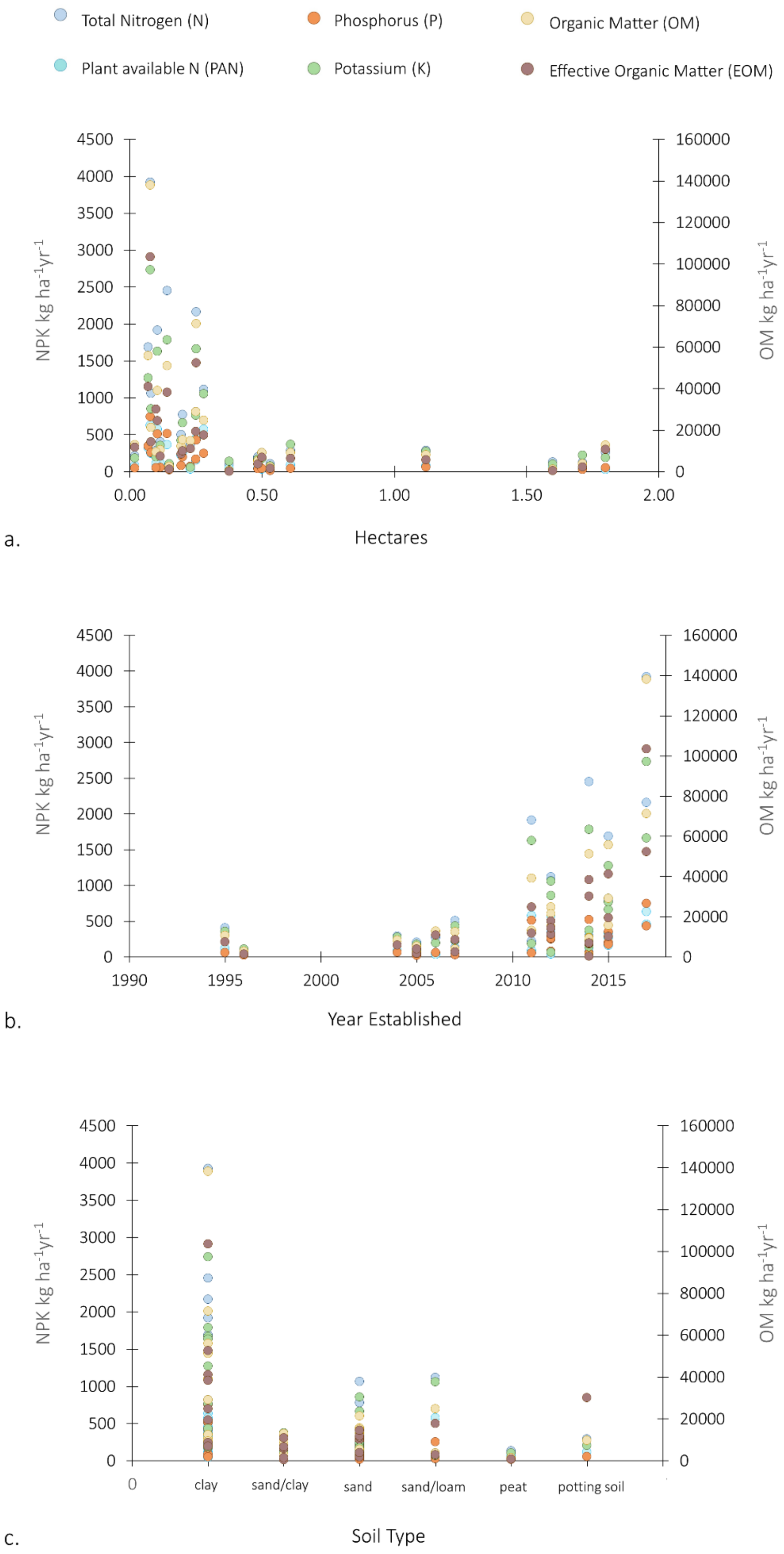

Figure 3. (a) Nitrogen (N), phosphorus (P) and potassium (K) and organic matter (OM) inputs plotted (a) against farms size, (b) year of farm establishment, and (c) per soil type

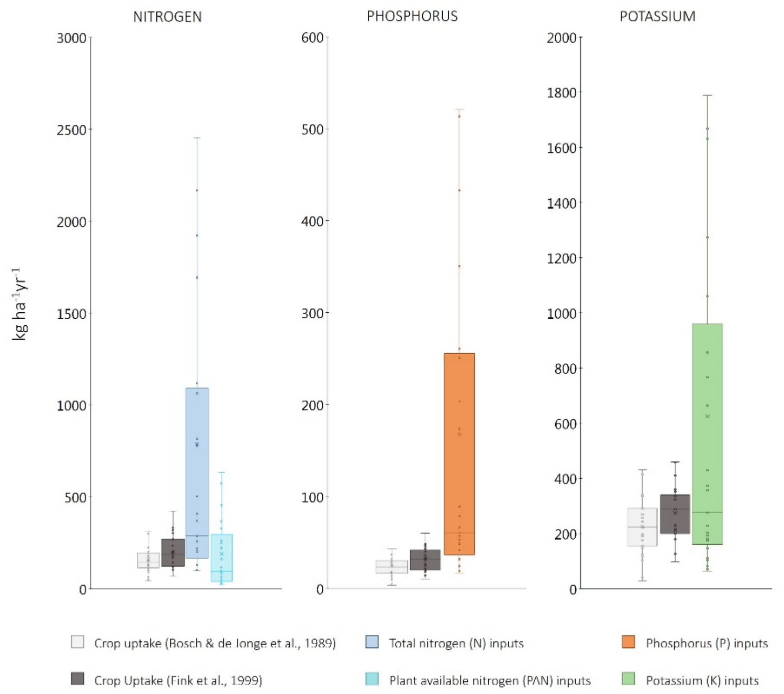

Figure 4. Nitrogen (N), phosphorus (P) and potassium (K) inputs of the 25 interviewed farms compared to NPK crop uptake retrieved from two studies (Bosch and De Jonge, 1989, Fink et al., 1999). Total N and plant-available N (PAN) inputs compared to crop uptake of N (a); P inputs compared to crop uptake of P (b); K inputs compared to crop uptake of K (c). Outliers (>1.5 interquartile range) excluded.

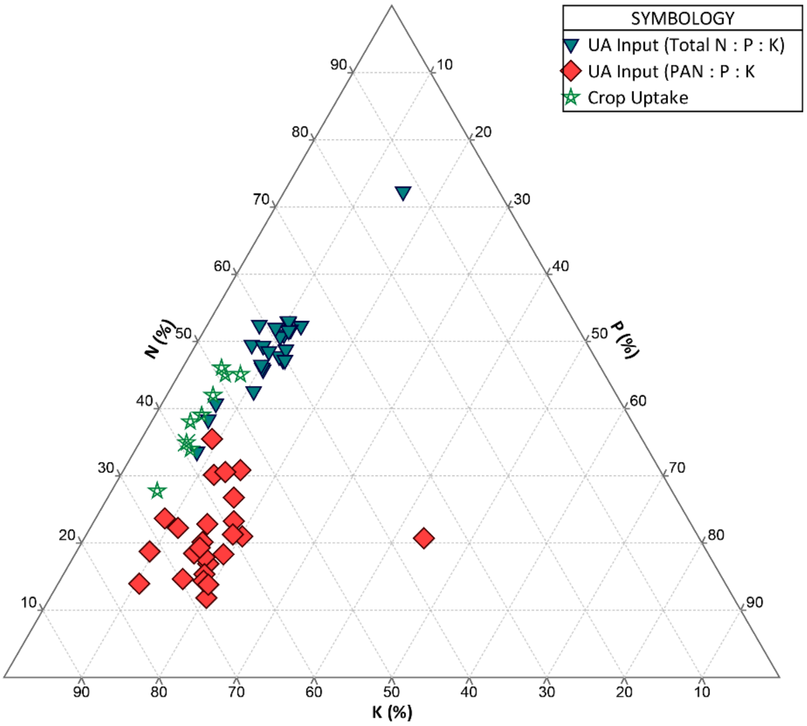

Figure 5. Comparison of ratios of nitrogen (N), phosphorus (P) and potassium (K) inputs (shown separately for total N and plant-available nitrogen (PAN)) for 25 UA farms with ratios of N, P and K uptake for 10 common crops grown on urban farms (beet root, broccoli, red cabbage, carrot, celery, green bean, lettuce, onion, radish and spinach). The ratios are normalized to percentages (e.g. N * $(N+P+K)^{-1}$). The N axis reads horizontally, the P axis reads diagonally from top right to bottom left and the K axis reads diagonally from bottom right to top left.

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