

Letter to the editors: Phyto-P-mining—secondary urban green recycles phosphorus from soils constructed of urban wastes

Thomas Nehls · Christophe Schwartz · Kye-Hoon John Kim ·
Martin Kaupenjohann · Gerd Wessolek · Jean-Louis Morel

Received: 7 March 2014 / Accepted: 6 November 2014 / Published online: 30 November 2014
© Springer-Verlag Berlin Heidelberg 2014

Abstract

Purpose Cities are hotspots of consumption of matter, energy, and water and hotspots of production of wastes, which are also secondary resources. Nutrients such as phosphorus are hardly extracted and recycled from these wastes, except from sewage sludge. This paper discusses a concept for the recycling of P from a great variety of urban wastes (phyto-P-mining).

Materials and methods Phyto-P-mining is based on the plant extraction of P from waste materials, which were used to produce planting substrates. They are intended for the greening of urban structures, which were de-vegetated during urbanization or which were not intended to be vegetated before (secondary urban green). After the newly established plants have extracted P, their biomass can be used to produce bioenergy (biogas, wood) or compost. Phosphorus could then be recycled from digestion residues and ashes or directly from compost.

Results and discussion Phyto-P-mining is based on otherwise wasted nutrients and on the greening of a high number of not

yet vegetated plots, including public or private plazas, sidewalks, roofs, and fallows. Greening is a major goal for urban planning, as functioning soil-vegetation-complexes provide ecosystem services such as climate regulation, dust absorption, wind brake, or aesthetic improvement. Especially in the dense inner city quarters, where vegetation is rare, new green improves public health and well-being. However, due to the lack of available horizontal but the high abundance of vertical structures like walls and facades in city centers, vertical green will be very important for phyto-P-mining. It can efficiently extract P from wastes due to its high ratio of biomass to ground area. Like the vertical areas, the vertical greens are often private properties. Although private greening is primarily conducted for social and cultural reasons, direct market benefits such as bioenergy or fertilizers may reduce costs for the greening. This will foster private urban greening to the benefit of the community and also the recycling of nutrients from urban resources.

Conclusions Phyto-P-mining based on secondary urban green will reestablish soil functions and natural cycling mechanisms in artificial urban systems. The approach has a great potential (i) to improve the urban living environments and to deliver benefits such as (ii) the recycling of phosphorus and other nutrients from urban wastes for the application in urban or rural agri- or horticulture and (iii) the ethically and ecologically sound production of bioenergy.

Keywords Constructed soils · Ecosystem services · Phosphorus recycling · Secondary urban green · Vertical green

Responsible editor: Rongliang Qiu

T. Nehls (✉) · G. Wessolek
Institute of Ecology, Chair for Soil Conservation, Technische
Universitaet Berlin, Ernst-Reuter-Platz 1, 10587 Berlin, Germany
e-mail: thomas.nehls@tu-berlin.de

C. Schwartz · J.-L. Morel
Laboratoire Sols et Environnement, Université de Lorraine, UMR
1120, 54500 Vandœuvre-lès-Nancy, France

C. Schwartz · J.-L. Morel
Laboratoire Sols et Environnement, INRA, UMR 1120,
54500 Vandœuvre-lès-Nancy, France

K.-H. J. Kim
Department of Environmental Horticulture, University of Seoul,
Seoul, Republic of Korea

M. Kaupenjohann
Institute of Ecology, Chair for Soil Science, Technische Universität
Berlin, Ernst-Reuter-Platz 1, 10587 Berlin, Germany

1 Introduction

In the phyto-P-mining approach (Fig. 1), plants are “utilized” to extract phosphorus from planting substrates, which are newly constructed from urban wastes. In the following, the prerequisites and boundary conditions for the concept are

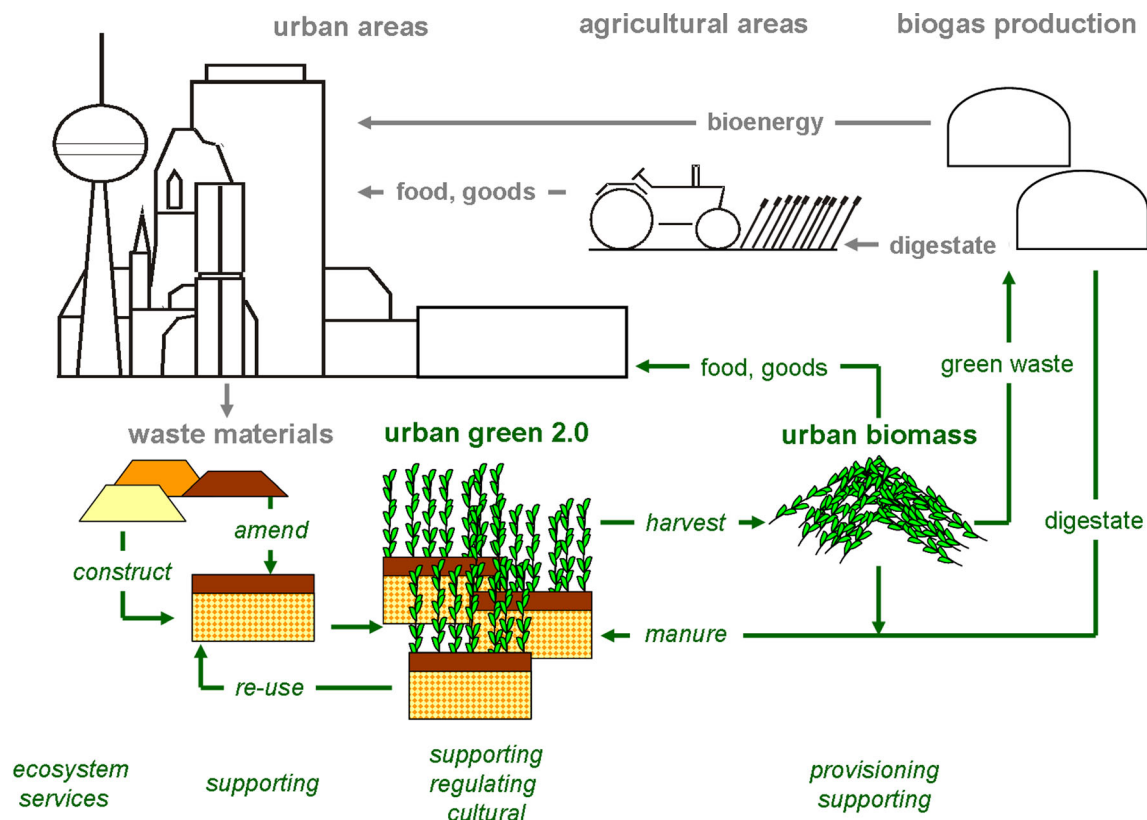


Fig. 1 The phyto-P-mining concept integrated into existing matter, energy fluxes, and infrastructures (gray arrows and objects). Waste materials are used as planting substrates for a high number of secondary urban

greens. The concept offers opportunities for biogas production and subsequent urban internal cycling as well as export of nutrients back to agricultural land (new matter and energy fluxes in green)

discussed exemplarily for the city of Berlin, then the concept itself is introduced and discussed.

1.1 Limited availability of phosphorus from geogenic sources

Recent agriculture mostly relies on mineral P fertilization. The availability of rock-phosphate-derived fertilizers is predicted to strongly decrease in the course of the next 50 to 300 years (Cordell et al. 2009; Van Kauwenbergh et al. 2013). The predicted period probably depends on the intention and focus of the authors. Rock phosphates are of geostrategic importance as almost 80 % (year 2013) of them are mined in only five countries: China (43%), USA (14%), Morocco (13%), Russia (6%), and Jordan (3%) (USGS 2014). Two strategies have been discussed to approach this shortage: (i) to improve the availability of P, which is already accumulated in agricultural top soils (Stutter et al. 2012), and (ii) to improve the efficiency and the recycling of P from fertilizers, manures, composts, and other wastes. There is a high recycling potential, as the global phosphorus cycle (e.g., UNEP 2011) is not a cycle at all. Closed cycles exist in natural ecosystems, but only partly in forestry and agriculture. Urban areas are the final parts in the food supply chain. From here on, P is lost mainly to dumpsites, river sediments, and the oceans, except for P in

sewage sludge. Sewage sludge as a soil amendment ($\approx 10\%$ in Poland to $\approx 70\%$ in the UK) remains relevant for the recycling of P and other nutrients (Sartorius 2012). However, its direct application will probably be replaced by engineering approaches to extract P from the sludge or its ashes (e.g., Adam et al. 2007; Scheidig et al. 2009). Techniques like FIX-PHOS and ASH DEC are expected to be profitable between 2015 and 2030 (Sartorius 2012). Finally, all other organic and inorganic urban waste materials should be examined for their P resource potential. It would be a successful adaptation of natural recycling concepts to use these waste materials to manufacture plant substrates and to “utilize” plants for P extraction (phyto-P-mining).

1.2 Availability of phosphorus from urban sources

As areas of concentrated import and consumption of goods, food, and energy, cities produce large amounts of waste. Some of these wastes can be used as mineral constituents and organic matter for the construction of planting substrates. In Germany, both are produced in remarkable amounts ($\text{g capita}^{-1} \text{ a}^{-1}$ with 80,585,700 inhabitants in Germany): concrete, bricks, tiles and ceramics (6.5×10^5), track ballast (2.7×10^4), soil material and stones (1.4×10^6), or street

sweeping (5.0×10^2), and organic material such as green wastes (6.6×10^4), biodegradable kitchen wastes (8.5×10^3), and organic household wastes (4.9×10^4). The latter are collected separately in a special bin and usually composted, but nowadays are increasingly used for biogas production (all data for the year 2012, not contaminated materials, Statistisches Bundesamt 2014).

In order to construct plant substrates from such wastes, the physical and chemical properties of the pure materials as well as the properties of its mixtures need to be known. Some materials like compost (e.g., Deportes et al. 1995) or bricks (e.g., Nehls et al. 2013) have already been studied. During the last decade, Séré et al. (2008, 2010) and Rokia et al. (2014) systematically and comprehensively investigated the construction of soils from urban waste materials. Based on feasibility and pedological criteria, they selected 25 binary and tertiary mixtures out of 220 theoretically possible mixtures (not considering the different mixing ratios) from eleven different components including nine waste materials (green waste, compost, street sweeping, sewage sludge, paper mill sludge, bricks, track ballast, rubble, concrete) and two soil materials. The study demonstrated that the investigated waste materials are appropriate to construct plant substrates. Mixtures of brick particles and compost are already in practical use as green roof substrates.

The total P contents of the mentioned waste materials range from 0.7 to 21 g kg⁻¹ for bricks and compost, while the available amounts (extracted according to Olsen) range from 0.03 to 1.1 g kg⁻¹ for bricks and green wastes, respectively (Rokia et al. 2014). So eight of the abovementioned nine waste materials (sewage sludge excluded) could substitute a share of 18 % (m/m) of the 1.2×10^{11} g of imported mineral fertilizer-P, which are applied to agricultural areas per year in Germany (7×10^3 g P ha⁻¹ a⁻¹).

1.3 Lack of soil, lack of urban green

Soils are sealed (Morel et al. 2014) and vegetation is regularly missing in dense inner city quarters, often showing fractions of impervious surfaces of 60 % and more (Shuster et al. 2005). For instance in Berlin, Germany, the highest impervious fraction of 69 % is measured in Friedrichshain-Kreuzberg, an inner city quarter, where the provision of green spaces per capita is the lowest (4.5 m²), while one of the lowest soil sealing fractions, 28 %, is measured in Spandau, a quarter with 30 m² of green space per capita (Umweltatlas Berlin, online). Pervious pavements are one strategy to partially reestablish the soil's filter and storage function (Nehls et al. 2008). However, these areas should also be greened as vegetation fulfills several additional provisioning, regulating, supporting, and cultural functions. For public health and well-being, the regulating ecosystem services such as cooling by shade and transpiration, and purification and moistening of the urban air

are of the highest relevance for inner city quarters. Important as well are cultural services like aesthetic reinforcement of the living surrounding, enhancement of the spiritual dimension, or recreation of city dwellers. Green structures are preferred over non-vegetated structures, positively co-notated and perceived as “beautiful,” relaxing and restorative (White and Gatersleben 2011), with the positive effects being more pronounced with increasing species richness (Fuller et al. 2007). The provisioning ecosystem services of green can be the production of food, fodder (for livestock farming, bees), cut flowers, biomaterials, medicines, and bioenergy.

However, there are also ecosystem disservices of plants, which are the more important the more inhabitants are affected: shading of flats by trees, spreading of allergens, smells, annoying leaves or insect secretions on the windshields of cars, provision of habitats for annoying singing-early-in-the-morning-especially-at-weekends-birds, but also for rats, spiders, and beetles. Depending on the design, urban green can also decrease the subjective perception of security (refreshing to read: Lyytimaki and Sipila 2009). These disservices should be seriously considered for the design and management of secondary urban green.

As the positive impact of urban green on human health and well-being is widely accepted (e.g., Tzoulas et al. 2007), it should be the aim of municipalities and inhabitants to increase the number of green spaces. In the following, we will discuss promising ways to reach that goal as a prerequisite to integrate phyto-P-mining.

1.4 New forms of urban green

Green areas such as parks are of limited spatial effectiveness concerning ecosystem services, e.g., climate regulation (Bowler et al. 2010). For the benefits of green, its abundance and visibility in the direct residential environment is crucial. Facade greening could be such a form of green. However, it is not as widespread as the proven ecosystem services would suggest (Ottele et al. 2010). So, often inner city inhabitants stand in front of their apartment blocks, greened roofs may be invisibly 20 m above and the next green park is some 100 m away. City planning should promote a high number of green spots, even small ones, which can form a city-wide green cover rather than to support only some parks or “nature” patches, which add only some green dots to the gray city fabric.

Obviously, especially former not vegetated surfaces should be greened (secondary green), as then the highest gain of ecosystem services can be achieved. Thus, it must be the goal to green paved surfaces, whether horizontal or vertical. As mentioned above, existing soils may have to be de-sealed, assessed for their suitability to grow plants (Moir and Thornton 1989; Kahle 2000; Abel et al. 2014) and probably ameliorated which all together can be costly. Instead,

constructed planting substrates in containers could be used (see below). New designs for such small-scale, horizontal, or vertical greening are needed as well as techniques for its irrigation and maintenance.

This small-scale greening can be privately financed which would be interesting as the financial resources of municipalities are usually limited. Additionally, most of the abovementioned spaces, especially the verticals, are private or rented properties and have long been outside the focus and beyond the direct reach of top-down urban planning. In this case, the whole private sector, inhabitants, companies, communities, associations, etc. should be included in the greening process (urban green 2.0). Thus, it would be possible to make people directly responsible for their own residential environment (Francis and Lorimer 2011). There are strong hints that city dwellers are willing to take that responsibility, as indicated by the renaissances of urban gardening and urban agriculture, or movements like guerilla gardening. This points to the rediscovered lust of city dwellers to experience and to learn how to cultivate plants in their living environment (Bendt et al. 2013). Often, this formerly suspiciously observed gardening activities are organized community based (Rosol 2010). Inhabitants should be provided with the participatory right to establish green in their direct living environment and with a reliable planning framework, which secures their investments (Francis and Lorimer 2011). Urban green 2.0 would guarantee that greening activities in the anthropocentric city are in accordance with the “cityzens” needs (see ecosystem disservices). It will develop a great variety of adapted greening strategies and designs (Dallimer et al. 2012), depending not only on the availability of space, water, and nutrients but also on regional or individual taste, financial resources, and needs of the neighborhood. One of these needs is the production of food for subsistence or the market. This importance will rise, as the world population will grow, especially in urban areas (Colding and Barthel 2013). The concurrence about land, water, and fertilizers for biofuel production will increase the pressure to value urban space and resources for food production (Godfray et al. 2010). Urban green can provide fibers, cut flowers, medicine, and biomass for fuel or energy production.

For example, Springer (2012) determined the biomass production of a city in the southern plains, USA to be 0.8 to 1.9×10^7 g DM ha⁻¹ a⁻¹ of planted land from lawn dethatching and mowing, leaf raking, and tree pruning. For facade green, no such data is available yet; therefore, it is estimated in the following based on data on biomass and available vertical areas for the example of Berlin, Germany. The typical vertical green species Boston ivy vine or Japanese creeper (*Parthenocissus tricuspedata*) produces organic dry matter (oDM) in amounts of 0.7 to 2.1×10^6 g oDM ha⁻¹ a⁻¹ of vertical area (Bartfelder and Köhler 1987). The potentially available vertical area of a city (facades, walls) can be estimated by remote sensing. For instance, Nehls (2010)

estimated a gable wall area/ground area ratio of 0.27 ha ha⁻¹ for the inner city quarters of Berlin (8000 ha ground area), which results in a total vertical area of 2160 ha. Thus, the potential to produce green biomass in the inner city of Berlin would be up to 4.5×10^9 g a⁻¹ or up to 0.6×10^6 g oDM ha⁻¹ a⁻¹ based on ground area. Note, that this would be only the production from gable walls without windows. In our opinion, the potential of urban areas to produce biomass is not adequately investigated and discussed yet, especially as these spaces are “unproductive.” Therefore, such biomass production would not be in concurrence to food production or nature preservation (see the debate on food or biofuel). In the following chapter, it will be discussed if the ecological prerequisites, especially the availability of planting substrates for such a productivity-oriented greening, are given in cities.

However, it must also be accepted that urban gardeners follow also goals different from production of food or biomass. They seek “meaningful” free time activity, recreation, education, communication, and the pleasure of working outside (Bendt et al. 2013). For instance, in the well-reported “Prinzessinnengarten” (prinzessinnengarten.net), an urban community garden project in Berlin, Germany, more than 1500 people grow plants at less than 0.6 ha. Obviously, the yield-oriented production or subsistence is the minor goal there.

1.5 Availability of space, water, and nutrients in urban areas

The ecological prerequisites for sustainable urban greening are space, water, and nutrients. They have to be reliably available, and in most cases, they are. Usually, the needed resources are even wasted or ignored: for the space, it is waste land, fallows, brown fields, yards, roofs, terraces, balconies, facades, or other vertical structures. While fallows and brown-fields may only be available for interim use, the vertical structures are available on a long-term perspective.

Water is often wasted in urban areas as waste water or rainwater runoff, and it is available in excess in case of raising groundwater tables (Gobel et al. 2004). Even in semi-arid and arid regions, it is possible to collect and store rain water from sealed surfaces to green at least small oasis patches. In the tropics and subtropics, the use of waste water can be of higher relevance (Pescod 1992) than in temperate regions, where urban greening can contribute to surface runoff reduction. In terms of rainwater, the temporal shift in availability and demand must be buffered by storages like cisterns. Knowledge on water demands of green roofs and vertical greens, which is needed to dimension such storages, is hardly available.

The next prerequisite for a sustainable urban green are nutrients, preferably provided by a soil or plant substrate. They are also available and are wasted if the city is seen as whole. However, in the highly sealed inner city quarters where

the secondary greening should be installed, there is a lack of soils. Using fertilizers or soil material from outside the city is not an option, as it would just enlarge the ecological footprint of the city. However, cities and their surroundings are areas of constant construction activity, suburbanization, and urban sprawl. Thus, soil material from construction activities could be used inside the cities. Their availability depends on legislative regulations, soil properties, their contamination status, and the market. Purpose-designed soil substitutes could be produced from locally available waste, the cities' secondary resources. However, in Berlin, with the beginning of biogas production from organic wastes in 2013, the availability of organic wastes for compost production decreased from $6.6 \times 10^{10} \text{ g a}^{-1}$ to only $1.0 \times 10^{10} \text{ g a}^{-1}$. The produced compost goes almost completely to rural agriculture (personal communication Kristian Kijewski, Berliner Stadtreinigung GmbH, 21.10.2014). For the Prinzessinnengarten in Berlin, starting compost production was the crucial and initial step for the garden. It is situated on paved and probably contaminated ground, so the plants are cultivated in containers. Today, the gardeners carefully select residues of organic food in the neighborhood and produce "organic" compost for themselves and for the market. Due to mineralization, nutrients, and carbon are lost from compost (Teemusk and Mander 2007). Growing substrates which copy natural soils in quantities of organic and inorganic constituents are more sustainable as reported for green roof substrates (Czemieli Berndtsson et al. 2009).

So, there is a need to produce new planting substrates or to ameliorate existing soils especially suited for food production or non-food greening purposes. The phyto-P-mining concept, introduced in the following, brings together all the aforementioned aspects.

2 The phyto-P-mining concept

For phyto-P-mining (Fig. 1), plants are grown to extract phosphorus from planting substrates, which were newly constructed from waste materials. Phyto-P-mining is not a single purpose concept but must be understood as a surplus benefit of the above discussed secondary urban greening strategy. It is especially suitable to exploit P from materials with comparable low P concentrations. In terms of maximum P extraction, the use of P hyperaccumulators, in other words, species and plant communities with high P extraction and luxury consumption like *Brassica napus* would be preferable. However, the plant or plant community should be chosen according to the primary function of the vegetation such as climatic regulation (shade, cooling by transpiration), food production (contaminant exclusion), ornamental purposes, or suitability to architecture as well as site-specific conditions

such as climate, light, and water availability. For phyto-P-mining, vertical green seems to be promising as it can reach higher biomass to ground area (rooted volume) ratios and thus higher extractions than horizontal green (see below).

The concepts to use the extracted P could be transferred from phytoremediation and hyperaccumulation of heavy metals by plants (e.g., Schwartz et al. 2003). To make the process profitable, Li et al. (2003) discuss not only to exploit the target metal but also to use the biomass for bioenergy production. Thus, the biomass produced from urban green, which was installed for other purposes (e.g., ornamental), becomes a resource itself. In the case of phyto-P-mining, the final use of the biomass should be the production of biogas or wood pellets. Both would guide matter and energy into established flow chains and existing infrastructures. In Germany, there were 7500 biogas plants already installed in 2012 and another 400 prognosticated for 2014 (Biogas e.V. 2013). They are then delivering about 5 % of the electricity demand of the country.

In the following, we estimate the bioenergy production of two model species and demonstrate their potential to contribute to P recycling, although both are rather used for other purposes than biogas production. The two species having a comparable high P uptake are rape (*B. napus*) for horizontal urban green and hop (*Humulus lupulus*) for vertical green. Due to harvest and storage losses, we assume 0.85 g g^{-1} of the above ground biomass of the model species to be converted to biogas. The organic dry matter yield for rape is around $3 \text{ to } 4 \times 10^6 \text{ g oDM ha}^{-1} \text{ a}^{-1}$, while for 4000 hop plants per hectare, it is $5.5 \text{ to } 6.5 \times 10^6 \text{ g oDM ha}^{-1} \text{ a}^{-1}$ (Heetkamp 2011). From rape and hop biomass, methane (given in standard liters, L_N , at air pressure of $1.013 \times 10^5 \text{ Pa}$ and air temperature of 273 K) can be produced in amounts of 262 and $212 L_N \text{ kg}_{\text{oDM}}^{-1}$ (Pettersson et al. 2007; Heetkamp 2011). For hop, with a usual inter- and intra-row spacing of 1.5 m and a height of the plants of 7 m, the virtual vertical greened area is $44.1 \text{ m}^2 \text{ m}^{-2}$ ground area, thus the yield per vertical area is about $1.2 \text{ to } 1.5 \text{ } 10^2 \text{ g m}^{-2}$. In order to use this biomass sustainably, adapted business models and harvesting strategies have to be developed.

With P concentrations in the biomass of $5 \text{ to } 7 \times 10^{-3} \text{ g g}^{-1}$ and $3 \text{ to } 4 \times 10^{-3} \text{ g g}^{-1}$ for rape and hop, respectively, both extract about $2 \text{ g P m}^{-2} \text{ a}^{-1}$. For hop, grown in containers, one can expect much higher extraction rates. Assuming a planting substrate container of 1 m^3 per plant (7 m high, $1.5 \times 10^3 \text{ g oDM}$), hop would extract up to $6 \text{ g P m}^{-2} \text{ a}^{-1}$ and thus up to three times the amount of horizontal plants, as discussed above.

The accruing amounts of biogas digestate (AD) and its P contents are intensively discussed topics in the bioenergy community. Mokry and Kluge (2009) found that the amount of AD is usually about 75 % (m/m) of the input for fresh green plant materials. The total P content of the digestate is usually $1.5 \text{ to } 2 \times 10^{-3} \text{ g g}^{-1}$ of which 60 to 70 % are water soluble.

Zirkler et al. (2014) and Moller and Muller (2012) found P accumulations of 16 to 25 % in the AD compared to the plant biomass, which is proportional to the dry mass reduction through digestion, while the availability of P was 20 to 47 % lower than that of the undigested material. Such data is not yet available for *H. lupulus* or other climbers like *Hedera helix*, *Parthenocissus tricuspidata*, and *Fallopia baldschuanica*.

The direct application of ADs as manures in agriculture is already practice (Mokry and Kluge 2009). Alternatively, P and other nutrients could be extracted and concentrated from the residues. Such techniques (Kuroda et al. 2012; Campos et al. 2014) are nowadays investigated due to rising amounts of digestate. The digestates of urban biomass could be used as fertilizers in (urban) agriculture and thus contribute to close nutrient cycles inside cities and between cities and their rural surroundings. Thus, not only the production of planting substrate but also the production of food and other plant products as well as the production of energy and fertilizers offer the possibility to enhance the economic benefits of phyto-P-mining.

3 Conclusions and outlook

The phyto-P-mining concept, that means waiving of geogenic P resources for urban greening, biomass, and food production (depending on the local needs and preferences), and the extraction of P from waste materials, which are seen as secondary resources, may provide a model approach to foster the sustainably use of P resources in urban areas. The main point of the concept is to base urban green on urban resources.

The approach is small-scale oriented and includes traditional forms of urban agriculture as well as new concepts. Small-scale, private sector-based urban greening (urban green 2.0) would influence neighborhoods both in terms of ecological inventory as well as their awareness towards food production, food security, food quality, and the environment in general. As also public spaces are influenced by private greening initiatives, it would improve community building and political activities—in short: participation. However, the approach may contain business aspects as well. It must be investigated, for whom and under which conditions urban green could be designed and managed in a profitable way. Production of biomass, bioenergy, and finally fertilizers might be important parts of the greening-connected value chain.

However, the concept as depicted in this letter also raises some questions of interest for soil science and urban planning. Analyzing and understanding a complex biogeochemical and physical construct like a soil and describing its functions is quite different from predicting characteristics of newly constructed soils. This experimental soil science or soil

engineering will contribute to our general understanding of soils. More specifically, first the feasibility of the phyto-P-mining concept must be investigated in terms of nutrient contents and availability from pure waste materials and mixtures. This should be done preferably by applying traditional chemical laboratory methods as well as plant experiments in pots but also on the field-scale. Scientific questions in that context concern medium and long-term availability of all relevant nutrients, not only P, nutrient leaching from the substrate by seepage water (eutrophication risk), and possible contamination of food and biomass (Deportes et al. 1995). Second, the substrates should be physically analyzed for self-compression, the development of structure (e.g., by biological activity) and pore system characteristics (e.g., water availability, air capacity), rooting, and erosion aspects.

The socioeconomic dimension of the approach includes the practical, organizational, and financial aspects. It is necessary to check the feasibility of the concept for a set of individual geographical and economical circumstances. Thereby, practice-oriented experiments under participation of urban gardeners would be helpful.

Acknowledgments We thank the French-German academic exchange program PROCOPE (DAAD and CAMPUS FRANCE), the German Science Foundation (DFG, FOR 1736), and the French ADEME-SITERRE program for financial support.

References

- Abel S, Nehls T, Mekiffer B, Wessolek G (2014) Heavy metals and benzo [a] pyrene in rubble soils. J Soils Sediments. doi:10.1007/s11368-014-0959-4 (this issue)
- Adam C, Kley G, Simon F-G (2007) Thermal treatment of municipal sewage sludge aiming at marketable P-fertilisers. Mater Trans 48(12):3056–3061
- Bartfelder F, Köhler M (1987) Experimentelle Untersuchungen zur Funktion von Fassadenbegrünungen, PhD thesis, Fachbereich 14 der Technischen Universität Berlin, Berlin
- Bendt P, Barthel S, Colding J (2013) Civic greening and environmental learning in public-access community gardens in Berlin. Landsc Urban Plan 109:18–30
- Biogas e.V. (2013) Branchenzahlen. online: http://www.biogas.org/edcom/webfvb.nsf/id/DE_Branchenzahlen/Sfile/13-11-11_Biogas%20Branchenzahlen_2013-2014.pdf (accessed at the 14.02.2014)
- Bowler DE, Buyung-Ali L, Knight TM, Pullin AS (2010) Urban greening to cool towns and cities: a systematic review of the empirical evidence. Landsc Urban Plan 97:147–155
- Campos A, Bilbao J, Zibek S, Stoll MS, Egner S, Hirth T (2014) Recovering organic and inorganic phosphorus compounds from solid constituents of residues by separating organic residues in solid and liquid phases, mixing solid phase with water and enzymatically converting organic to inorganic phosphates. Patent. Patent Number(s): DE102012220810-B3, Fraunhofer Ges Foerderung Angewandten e.V (Frau-C), Derwent Primary Accession Number: 2014-C88549 [14]
- Colding J, Barthel S (2013) The potential of 'Urban Green Commons' in the resilience building of cities. Ecol Econ 86:156–166

- Cordell D, Drangert J-O, White S (2009) The story of phosphorus: global food security and food for thought. *Glob Environ Chang* 19:292–305
- Czemiel Berndtsson J, Bengtsson L, Jinno K (2009) Runoff water quality from intensive and extensive vegetated roofs. *Ecol Eng* 30:271–277
- Dallimer M, Irvine KN, Skinner AMJ, Davies ZG, Rouquette JR, Maltby LL, Warren PH, Armsworth PR, Gaston KJ (2012) Biodiversity and the feel-good factor: understanding associations between self-reported human well-being and species richness. *Bioscience* 62: 47–55
- Deportes I, Benoit-Guyod J-L, Zmirou D (1995) Hazard to man and the environment posed by the use of urban waste compost: a review. *Sci Total Environ* 172:197–222
- Francis RA, Lorimer J (2011) Urban reconciliation ecology: the potential of living roofs and walls. *J Environ Manag* 92:1429–1437
- Fuller RA, Irvine KN, Devine-Wright P, Warren PH, Gaston KJ (2007) Psychological benefits of greenspace increase with biodiversity. *Biol Lett* 3(4):390–394
- Gobel P, Stubbe H, Weinert M, Zimmermann J, Fach S, Dierkes C, Kories H, Messer J, Mertsch V, Geiger WF, Coldewey WG (2004) Near-natural stormwater management and its effects on the water budget and groundwater surface in urban areas taking account of the hydrogeological conditions. *J Hydrol* 299:267–283
- Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C (2010) Food security: the challenge of feeding 9 billion people. *Science* 327:812–818
- Heetkamp J (2011) Biogasanlage Wolnzach (Hallertau) - Regenerative Energie aus Hopfenrebenhäckseln. DWA Energietage-Biogas Kassel 14.-16.11.2011. online: http://de.dwa.de/tl_files/_media/content/PDFs/Abteilung_BiZ/Energietage2011/Tag_3/pp-Heetkamp.pdf (accessed at the 04.07.2014)
- Kahle P (2000) Heavy metals in garden soils from the urban area of Rostock (Schwermetallstatus Rostocker Gartenböden). *J Plant Nutr Soil Sci* 163:191–196
- Kuroda M, Yuzawa M, Komori M (2012) Recovery of phosphorus in waste liquid and purification of biogas from methane fermentation of organic waste, involves immersing iron in liquid containing phosphorus, contacting phosphate suspension with biogas, and recovering phosphate. Patent. Patent Number(s): JP2012024696-A, Patent Assignee Name(s) and Code(s): DAIWA Setsubi Koji KK (DAIW-Non-standard), Derwent Primary Accession Number: 2012-B67240 [14]
- Li YM, Chaney R, Brewer E, Roseberg R, Angle JS, Baker A, Reeves R, Nelkin J (2003) Development of a technology for commercial phyto extraction of nickel: economic and technical considerations. *Plant Soil* 249:107–115
- Lyytimäki J, Sipilä M (2009) Hopping on one leg—the challenge of ecosystem disservices for urban green management. *Urban For Urban Green* 8:309–315
- Moir A, Thornton I (1989) Lead and cadmium in urban allotment and garden soils and vegetables in the United Kingdom. *Environ Geochem Health* 11(3–4):113–119
- Mokry M, Kluge R (2009) Inhaltsstoffe von Gaerprodukten sowie Möglichkeiten zu ihrer geordneten pflanzenbaulichen Verwertung. *Landinfo* 5(2009):1–5
- Moller K, Muller T (2012) Effects of anaerobic digestion on digestate nutrient availability and crop growth: a review. *Eng Life Sci* 12(3): 242–257
- Morel J-L, Chenu C, Lorenz K (2014) Ecosystem services provided by soils of urban, industrial, traffic, military and mining areas (SUITMAs). *J Soils Sediments*. doi:10.1007/s11368-014-0926-0 (this issue)
- Nehls T (2010) Ungenutztes Flächenpotenzial für die Fassadenbegrünung am Beispiel Berlins. Bauwerksbegrünung. Verlag Kuberski, Stuttgart pp 74–75
- Nehls T, Jozefaciuk G, Sokolowska Z, Hajnos M, Wessolek G (2008) Filter properties of seam material of paved urban soils. *Hydrol Earth Syst Sci* 12:691–702
- Nehls T, Rokia S, Mekiffer B, Schwartz C, Wessolek G (2013) Contribution of bricks to urban soil properties. *J Soils Sediments* 13:575–584
- Ottele M, van Bohemen HD, Fraaij ALA (2010) Quantifying the deposition of particulate matter on climber vegetation on living walls. *Ecol Eng* 36:154–162
- Pescod MBW (1992) The urban water cycle, including waste-water use in agriculture. *Outlook Agric* 21(4):263–270
- Pettersson A, Thomsen MH, Hauggaard-Nielsen H, Thomsen A-B (2007) Potential bioethanol and biogas production using lignocellulosic biomass from winter rye, oilseed rape and faba bean. *Biomass Bioenergy* 31:812–819
- Rokia S, Séré G, Schwartz C, Deeb M, Fournier F, Nehls T, Damas O, Vidal-Beaudet L (2014) Modelling agronomic properties of Technosols constructed with urban wastes. *Waste Manag* 34(11): 2155–2162
- Rosol M (2010) Public participation in post-fordist urban green space governance: the case of community gardens in Berlin. *Int J Urban Reg* 34:548–563
- Sartorius C (2012) Secondary phosphate. POLINARES Working Paper No. 22, online: http://www.polinares.eu/docs/d2-1/polinares_wp2_chapter10.pdf (accessed at the 14.02.2014)
- Scheidig K, Schaaf M, Mallon J (2009) Profitable recovery of phosphorus from sewage sludge and meat & bone meal by the Mephrec process—a new means of thermal sludge and ash treatment. In: Ashley K, Mavinic D, Koch F (eds) International Conference on Nutrient Recovery from Wastewater Streams. IWA Publishing, London. ISBN 1843392321
- Schwartz C, Echevarria G, Morel JL (2003) Phytoextraction of cadmium with *Thlaspi caerulescens*. *Plant Soil* 249:27–35
- Séré G, Schwartz C, Ouvrard S, Sauvage C, Renat J-C, Morel J-L (2008) Soil construction: a step for ecological reclamation of derelict lands. *J Soils Sediments* 8:130–136
- Séré G, Schwartz C, Ouvrard S, Renat JC, Watteau F, Villemin G, Morel JL (2010) Early pedogenic evolution of constructed Technosols. *J Soils Sediments* 10:1246–1254
- Shuster WD, Bonta J, Thurston H, Warnemuende E, Smith DR (2005) Impacts of impervious surface on watershed hydrology: a review. *Urban Water J* 2:263–275
- Springer TL (2012) Biomass yield from an urban landscape. *Biomass Bioenergy* 37:82–87
- Statistisches Bundesamt (2014) Umwelt Abfallbilanz 2012 Report. Statistisches Bundesamt Wiesbaden, Germany online: https://www.destatis.de/DE/ZahlenFakten/GesamtwirtschaftUmwelt/Umwelt/UmweltstatistischeErhebungen/Abfallwirtschaft/Tabellen/Abfallbilanz2012.pdf?__blob=publicationFile (accessed at the 24.11.2014)
- Stutter MI, Shand CA, George TS, Blackwell MSA, Bol R, MacKay RL, Richardson AE, Condrón LM, Turner BL, Haygarth PM (2012) Recovering phosphorus from soil: a root solution? *Environ Sci Technol* 46:1977–1978
- Teemusk A, Mander Ü (2007) Rainwater runoff quantity and quality performance from a greenroof: the effects of short-term events. *Ecol Eng* 30:271–277
- Tzoulas K, Korpela K, Venn S, Yli-Pelkonen V, Kazmierczak A, Niemela J, James P (2007) Promoting ecosystem and human health in urban areas using green infrastructure: a literature review. *Landsc Urban Plan* 81:167–178

- Umweltatlas Berlin (online) Senatsverwaltung für Stadtentwicklung Berlin, <http://www.stadtentwicklung.berlin.de/umwelt/umweltatlas/> (accessed at the 14.02.2014)
- United Nations Environmental Programme (2011) UNEP Year Book 2011: Emerging issues in our global environment—phosphorus and food production, Nairobi, Kenya, online: <http://www.unep.org/yearbook/2011/> (accessed at the 14.02.2014)
- U.S. Geological Survey (2014) Mineral Commodity Summaries 2014. Part Phosphate Rock, pp 118–119, U.S. Geological Survey, 196p
- Van Kauwenbergh SJ, Stewart M, Mikkelsen R (2013) World reserves of phosphate rock... a dynamic and unfolding story. *Better Crops* 97: 18–20
- White EV, Gatersleben B (2011) Greenery on residential buildings: does it affect preferences and perceptions of beauty? *J Environ Psychol* 31:89–98
- Zirkler D, Peters A, Kaupenjohann M (2014) Elemental composition of biogas residues: variability and alteration during anaerobic digestion. *Biomass Bioenergy* 67:89–98