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RESEARCH ARTICLE

Rooftop farming on urban waste provides many ecosystem services

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Abstract
Urban farming, especially on rooftops, is a popular and growing topic in both the media and the scientific literature, providing a genuine opportunity to meet some of the challenges linked to urban development worldwide. However, relatively little attention has been paid to date to the growing medium of green roofs, i.e., Technosols. A better understanding of the influence of Technosols and the link with ecosystem services is required in order to maximize the environmental benefits of urban rooftop farming. Between March 2013 and March 2015, a pilot project called T4P (Parisian Productive rooftoP, Pilot Experiment) was conducted on the rooftop of AgroParisTech University. Urban organic waste was used, and results were compared with those obtained using a commercial potting soil, based on yield and trace metal concentrations, substrate characterization, and the amount of leaching. An assessment of the ecosystem services expected from the Technosols was undertaken in terms of the output of food (food production and quality), regulation of water runoff (quantity and quality), and the recycling of organic waste. Indicators of these ecosystem services (e.g., yield, annual loss of mass of mineral nitrogen) were identified, measured, and compared with reference cases (asphalt roof, green roof, and cropland). Measured yields were almost equivalent to those obtained from horticultural sources in the same area, and the Technosols also retained 74–84% of the incoming rainfall water. This is the first quantitative analysis of ecosystem services delivered by urban garden rooftops developed on organic wastes, and demonstrates their multifunctional character, as well as allowing the identification of trade-offs. An ecosystem services approach is proposed for the design of soil-based green infrastructure of this kind and more generally for the design of sustainable urban agriculture.

Keywords Urban farming · Ecosystem services · Technosol · Urban waste · Green roof · Urban garden · Productive rooftop · Green infrastructure

1 Introduction

The last decade has seen an increasing level of interest in urban agriculture (Specht et al. 2013). Urban agriculture can be defined as "an industry located within or on the fringe of a town, a city or a metropolis, which grows or raises, processes and distributes a diversity of food and non-food products, (re-)using largely human and material resources, products and services found in and around that urban area, and in turn supplying human and material resources, products and services largely to that urban area" (Mougeot 2000). Urban agriculture is often considered as an opportunity to improve nutrition and food security in urban areas as well as to provide social value and environmental benefits (Lin et al. 2015). It is also a response to increasing demands from urban dwellers for local produce. Among the many forms of urban agriculture, productive rooftops based on substrate have emerged as an efficient solution given the lack of space in many cities (Orsini et al. 2014). This form is also known as "building-integrated non-conditioned urban agriculture" (Goldstein et al. 2016) to distinguish it from building-integrated conditioned farms such as hydroponic farms under greenhouses.

1.1 Urban agriculture as green infrastructure

Substrate-based productive rooftops are a type of green infrastructure. According to Gómez and Barton (2013), the term "green infrastructure" "captures the role that water and

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vegetation in or near the built environment play in delivering ecosystem services at different spatial scales (building, street, neighborhood, region).” An increasing body of the literature demonstrates that green infrastructure can offset some of the negative impacts of urban areas. Among green infrastructure, green roofs have been developing rapidly; in consequence, they are increasingly being studied for their many benefits (Berardi et al. 2014). They offer great potential in that roofs in cities in particular represent large and undervalued surface areas. Indeed, roof areas can represent up to 32% of the horizontal surface of built-up areas (Oberndorfer et al. 2007). Several authors have examined the environmental benefits provided by green roofs, with the majority focusing on extensive vegetated roofs planted with short, drought-resistant species (see the review by Cook-Patton and Bauerle (2012)). However, because most of these studies focus on one particular benefit at a time, a comprehensive assessment is still needed to identify all the benefits and drawbacks in a comprehensive way.

1.2 Ecosystem services as a framework analysis

The required broad-based assessment of green infrastructure can be provided by an ecosystem services framework, as previously demonstrated in urban ecosystems (Gómez-Baggethun and Barton 2013). Ecosystem services are the benefits that human societies derive from ecosystem functioning (Millenium Ecosystem Assessment 2005). Most of the ecosystem services provided by cities result from the presence of green infrastructure (Gómez-Baggethun and Barton 2013). Vegetated rooftop ecosystems could provide services such as water flow regulation and runoff mitigation, urban temperature regulation, air purification, waste assimilation and recycling, regulation of the global climate, pollination, mitigation against the loss of natural biodiversity, esthetic satisfaction, access to recreation, and even, in the case of productive rooftops, the provision of food (Cook-Patton and Bauerle 2012; Gómez-Baggethun and Barton 2013). To date, the potential of green roofs for water retention (Czemiel Berndtsson 2010), the reduction of air pollution (Yang et al. 2008), noise abatement, carbon sequestration, and thermal regulation (Li and Babcock 2014) have been examined extensively for rooftops, but the concept of ecosystem services is still barely used in the case of vegetated rooftops, as discussed by Luederitz et al.(2015).

To our knowledge, quantitative assessment of the ecosystem services provided by productive rooftops has not yet been undertaken; although they are designed to grow vegetables, they differ from vegetated rooftops in several ways. First, to grow plants on substrates, soils are created de novo on these roofs from a variety of materials such as topsoil and/or organic waste (Oberndorfer et al. 2007); these are known as constructed Technosols (Rossiter 2007). Second, the constraints differ from those that affect non-productive rooftops (Eksi et al. 2015). Because food production is the primary objective, an adequate provision of nutrients is required, together with the appropriate water-retaining capacity and related physical characteristics. Nutrients can be provided either by mineral fertilizers, which can lead to nutrient loss (Rowe 2011), or by a substrate rich in organic matter such as compost (Grard et al. 2015). A few authors have investigated the potential of extensive green rooftops for crop production (Whittinghill et al. 2013) or the potential of rooftops for food production, i.e., the production potential of growing systems using substrate made of potting soil amended with compost and fertilizer (Orsini et al. 2014) or using compost mixed with sand (Eksi et al. 2015). Sanyé-Mengual et al. (2015) showed that the environmental impact and economic cost were lower for soil-based production on rooftops than in a rooftop greenhouse. However, no studies have yet been devoted to soil as a critical component in the functioning and environmental impacts of productive vegetated rooftops.

1.3 Productive rooftops and Technosols

Despite the fact that soils contribute substantially to urban ecosystem services via several functions, they are generally overlooked (Morel et al. 2014). Compared to classical Technosols at ground level (either constructed or resulting from deposits), constructed Technosols on productive rooftops have to meet specific technical requirements (e.g., related to the load capacity of the roof) in addition to the expected function of supporting plant growth. The use of local materials such as urban organic waste in these soils offers multiple advantages: (1) it avoids the consumption of non-renewable resources such as peat or the transport of rural soils to cities; (2) it avoids the costs incurred and the harmful greenhouse gases generated by the transport and treatment of organic waste; (3) benefit is gained from the nutrients contained in organic waste, thereby reducing the consumption of mineral fertilizers; and (4) the materials can be lightweight. Potential disadvantages include substrate shrinkage, nutrient loss through storm water runoff, and carbon dioxide emissions through substrate respiration. Consideration of these constraints highlights the need for research into Technosol design for productive rooftops and the optimization of ecosystem services.

1.4 Ecosystem services evaluation

While the quantification of ecosystem services is a necessary step in ensuring their proper consideration in management decision-making, current debates reflect the absence of any consensus regarding the methods of biophysical evaluation to be used for ecosystem services (see the review by Boerema et al. (2016)). Referring to the ecosystem services cascade defined by Haines-young and Potschin (2010) in which ecosystem properties (biophysical properties or stocks) produce ecosystem functions (flows) that provide ecosystem services and these in turn benefit humans and may be ascribed an economic value, Boerema et al. (2016) recommend that flows or benefits rather than stocks alone be measured in any biophysical evaluation. Ecosystem services are usually evaluated using indicators as proxy measures, and many indicators have been proposed and discussed (e.g., Kandziora et al. (2013)). While several authors express indicators as absolute values, others define the provision of ecosystem services in relative terms compared with a reference, which could be an optimal case (e.g., Van Wijnen et al. (2012)). The selection of an appropriate reference is thus critical, and its influence on the evaluation must be considered.

From the research gaps outlined above, our aim was to evaluate the ecosystem services provided by productive open-air rooftops where the Technosols are based on recycled urban organic waste alone. We used a productive rooftop experiment (Grard et al. 2015) with a focus on constructed Technosols. Among the potential ecosystem services supplied by productive rooftops, we focused on four services: (1) food supply, (2) water flow regulation and runoff mitigation, (3) regulation of runoff water quality, and (4) assimilation and recycling of organic waste. These services were chosen in view of their importance per se, as well as an expectation that the characteristics of Technosols favor these services in particular. We measured indicators of the different ecosystem services over the course of a 2-year experiment, comparing the provision of ecosystem services to that used in other systems adapted to rooftop- or land-based vegetable production. To our knowledge, this is the first evaluation of multiple ecosystem services provided by productive rooftops.

2 Materials and methods

2.1 Pilot rooftop experiment

The pilot experiment is located on the flat roof of a five-story building called "Bertrand Ney" at AgroParisTech University in Paris, France (48° 50′ 24.4″ N, 2° 20′ 54.5″ E) (Fig. 1). The three main principles of the T4P experiment are that it should (Grard et al. 2015):

1. be transposable to people without specific agricultural skills and with limited economic resources, with the overarching objective of being able to "mimic" a community garden on the roof;
2. be based only on the use of local urban organic waste as a part of an urban metabolism (Barles 2009); and
3. avoid the use of fertilizers and chemical pesticides in order to limit the contamination of food products and the ecosystem.

Fig. 1 Upper panel: Overview of the rooftop of AgroParisTech in March 2015. Image by David Haddad.com with permission. Lower panel, left: Experimental devices in April 2013. Image by Baptiste Grard with permission. Lower panel, right: Top view of an experimental plot with the drip irrigation system in April 2014. Image by Baptiste Grard, with permission

Vegetables were grown in wooden boxes (90 × 90 × 40 cm) typically used as backyard composters and separated from each other by at least 50 cm. The Technosols were surrounded by a geotextile membrane extending to the top of the box. An impermeable membrane lined the bottom of each box, allowing water to be stored beneath the Technosol in a 5-cm-deep volume filled with clay balls, which acted as a reservoir of water. An evacuation pipe at the top of the reservoir directed the overflow water to a collection tank (Fig. 2a).

Urban organic wastes were used as substrates to create the Technosol, which was a compost made of green waste from public parks and private gardens in the city, as well as crushed wood from the city gardens and parks, both provided by our partner *Bio Yvelines Services*. Potting soil was used as a reference. Parent materials were analyzed by the soil laboratory of INRA Arras for pH_{water} (ratio soil/solution = 1/5 *v*/*v*)—NF ISO 10390, organic carbon content (dry combustion by heating at 1000 °C with O_2)—NF ISO 10694, and total nitrogen (dry combustion by heating at 1000 °C with O_2)—NF ISO 13878. Dry bulk density was measured according to NF EN 13041. Volumetric mass density was measured at pF1 (EN 13041) with 0.8 ± 0.2, 1.0, and 0.3 ± 0.02 g cm^{-3} for compost of green waste, potting soil, and crushed wood, respectively.

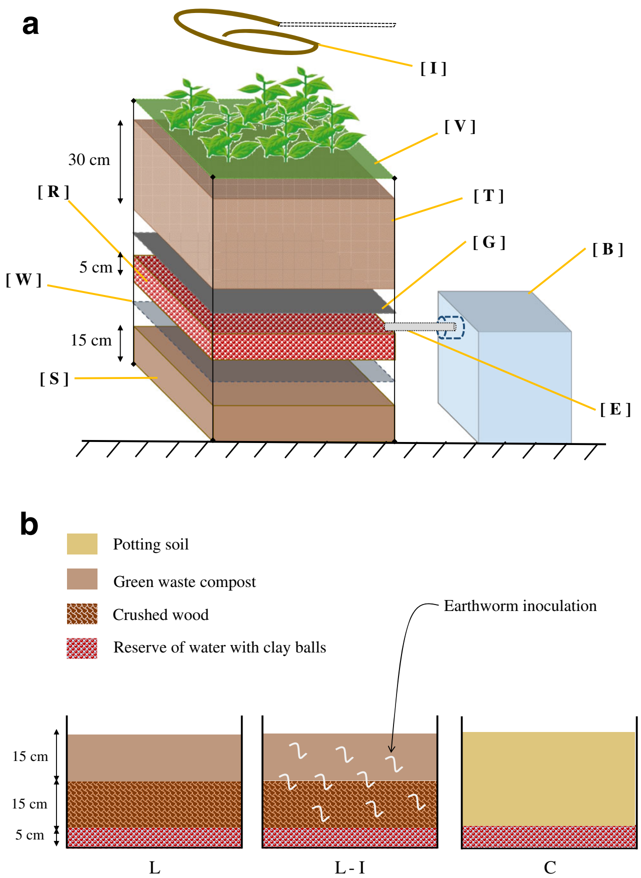

Fig. 2 **a** Schematic drawing of experimental box. Legend: [B] bottle storage for the overflow of water, [E] evacuation, [G] geotextile, [I] drip irrigation system, [R] reserve of water with clay balls, [S] wooden pieces to raise the box, [T] Technosol, [V] vegetation layer, and [W] waterproof membrane. **b** Description of the three treatments of the experiment

The main chemical characteristics of the organic waste are presented in Fig. 3. Four trace metals (Cd, Pb, Cu, and Zn) currently found in polluted urban garden soils were analyzed in the parent material and in one harvest of tomatoes and lettuces during the first year. Prior to analysis, the soil samples were air-dried (40 °C) for at least 2 weeks and sieved. A Polarized Zeeman Atomic Absorption spectrophotometer model Z5000 (HITACHI) was used for electrothermal atomic absorption spectrometry (ETAAS) to determine Cd, Pb, and Cu and for flame atomic absorption spectrometry (FAAS) to determine Zn. All measurements were performed on samples in triplicate.

Three different units were setup in March 2013, each with three replicates (Fig. 2b):

- Lasagna (L): a 15-cm layer of green waste compost covered with a 15-cm layer of crushed wood.
- Lasagna inoculated (L-I): a 15-cm layer of green waste compost covered with a 15-cm layer of crushed wood, in which we inoculated adult earthworms belonging to 3 species and 2 ecological categories: 15 *Dendrobaena veneta* individuals (epigeic earthworm), 35 *Eisenia fetida* (epigeic earthworm), and 10 *Lumbricus terrestris* (epi-anecic earthworm). Inoculation densities were lower than usual practice according to Pey et al. (2014). After a year, only *Eisenia fetida* survived with a high rate of reproduction.
- Control (C): 30 cm of potting soil.

Finally, woodchips (0–40 mm; Fig. 2b) were placed as a mulch on top of the Technosol to reduce evaporation (24 l of mulch per box each growing season).

The control was introduced to compare the performance of the Technosol organic waste with that of a reference frequently used in horticulture, and earthworms were inoculated with the hypothesis that they would modify the ecosystem services by accelerating the biodegradation of organic waste and creating biopores. *Eisenia fetida* and *Dendrobaena veneta* were selected with this in mind because they inhabit organic-rich materials, and both species are commonly used in laboratory experiments. *Eisenia fetida* is a robust earthworm species with good tolerance of a range of temperatures and humidities, which is also the case for *Dendrobaena veneta* but to a lesser extent. *Lumbricus terrestris* was selected because of its characteristics as an ecosystem engineer, which could affect the soil structure.

The structure of our boxes shares common elements with that used in standard green roofs (Oberndorfer et al. 2007), having a vegetation layer, a growing medium, a membrane layer (named geotextile in our case), and a waterproofing layer. However, our system also has three main differences from standard green roofs: first, we used wooden boxes in order to create accessible spaces and to distribute the weight on the roof and limit overloading. Second, we used a waterproof membrane to ensure the presence of a water storage volume, which additionally separated the contents of the box from the roof. Third, the proportion of compost in our experimental boxes greatly exceeded the standard proportion of organic matter recommended for non-productive green roofs. Usually, less than 20% of compost by volume is recommended due to possible negative impacts (mostly nutrient leaching), despite the potential advantages in terms of water retention capacity and biomass production (Eksi et al. 2015).

In March 2014, after a single cropping season, an important substrate shrinkage effect was observed in all cases. To compensate for this loss due to biodegradation and/or substrate compaction, we refilled the boxes to a height of 30 cm with either green waste compost (L and L-I) or potting soil (C). Hence, in March 2014, 88 l of compost were added per box to L, 122 l of compost to L-I, and 75 l of potting soil to C. Between the two growing seasons, the undecomposed mulch was removed before refilling the boxes, before being subsequently returned.

During dry periods, the boxes were irrigated using a dripping tap system with tap water. The volume used for irrigation

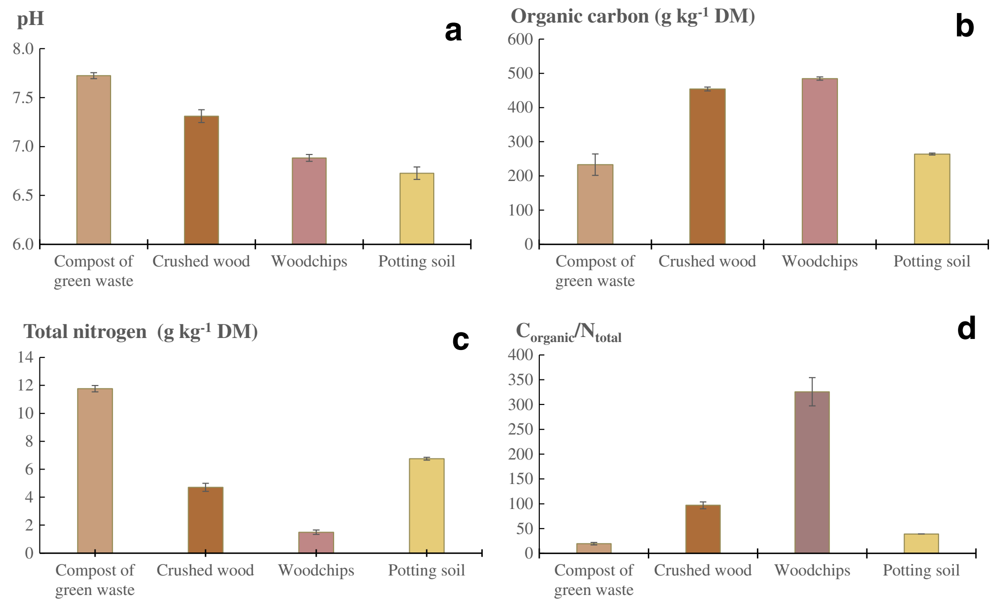

Fig. 3 Characteristics of the organic waste used in the experiment. Mean and standard error based on three replicates

was measured by a water meter. At the onset of the experiment in March 2013, we sampled cores from each layer. Both the sampled cores and the initial organic waste were air-dried and ground to 200 μm prior to analysis at the soil laboratory of INRA Arras as described above.

The succession of cultures took place as follows:

– March to April 2013 and 2014: five units of lettuce (*Lactuca sativa*) per box,
– May to mid-October 2013 and 2014: four units of cherry tomatoes (*Lycopersicum esculentum* var. cherry) per box, and
– Mid-October to March 2014 and 2015: green manure (*Trifolium incarnatum* and *Secale cereale*).

At harvest, shoots and roots were returned to the soil. Green manure was left to decompose on the surface of the soil. Notably, plant densities were quite low compared to those achieved by professional producers in the Ile-de-France region [personal communication with a farmer].

2.2 Meteorological data

Temperature, wind speed, solar radiation, and rainfall were recorded at the nearby meteorological station of the "Meteo France" network. This station is situated at Montsouris Park in Paris (48° 49′ 18″ North and 2° 20′ 16″ East), approximately 2.5 km from the experimental roof.

Weather patterns were similar between the two growing seasons in terms of average temperature and solar radiation. However, annual precipitation differed greatly between the 2013–2014 and 2014–2015 growing seasons, at 584 and 687 mm, respectively. The distribution of rainfall also differed, with higher amounts recorded in April, June, July, August, and December in 2014–2015 and less in May and September.

2.3 Ecosystem services evaluation

To achieve our aim of a full biophysical evaluation, we first identified the ecosystem services that might be expected from productive rooftops. We selected a subset of ecosystem services for which the characteristics of Technosols would be determinant and which could be quantified using our experimental devices. We then identified the processes or functions generating the particular service, before selecting a corresponding indicator based on the literature. Finally, we chose a reference case to be compared with the rooftop for each service (see below).

The analytical framework is presented in Table 1. The choice of indicators, methods, and references for each ecosystem service is detailed below. All results are expressed per square meter of experimental unit. Because the experimental boxes occupied less than 1 m^2 of the surface area (0.81 m^2), for all the variables, we assumed a linear relationship between our boxes and a similar box with a surface area of 1 m^2.

2.3.1 Indicator for food supply (quantity and quality)

Each element of edible biomass was harvested and weighed to measure the yield. Prior to analysis, the harvests were dried to 60 °C for at least 2 weeks. Results for trace metal elements in lettuces and tomatoes (Table 2) refer to fresh weight, with lettuce having 3% dry matter and tomatoes 8%. Methods to quantify trace metal elements in vegetables were the same as

Table 1 Evaluated ecosystem services and their indicators

Ecosystem services			Indicator	Processes	References
Provisioning services	Food supply	Food quantity	Production of food (kg fresh weight m^{-2} $year^{-1}$)	Primary production, anchoring and good physical conditions for roots, provision of water and nutrients, beneficial organisms, pest control	Productive rooftop or cropland
		Food quality	Concentration of trace metal element (mg kg^{-1} of fresh matter)	Vegetables absorption, atmospheric deposition, or water contamination	Quality standards
Regulating services	Water flow regulation	Quantity	% of rain water catch	Water infiltration, evapotranspiration, retention, and drainage	Bare/asphalt roof and/or green roof
		Quality	Weighted average concentration of TOC, TIC, $NO^-{}_3$, and $NH^+{}_4$	Retention of elements and molecules, leaching, biodegradation	Bare/asphalt roof and/or green roof and quality standards
	Urban waste regulation	Storage and recycling	Waste used (kg m^{-2} $year^{-1}$)	Biodegradation and substrate shrinkage	Bare/asphalt roof and/or green roof
	Carbon storage	Storage	C (kg m^{-2})	Biodegradation	Bare/asphalt roof and/or green roof

those for soil samples (see the "Pilot rooftop experiment" section).

2.3.2 Indicator for water leaching (quantity and quality)

Throughout the 2 years of the experiment, water was collected 4 days at most after it had leached from the reservoir to the collecting bottle (Fig. 2). The volume of leachate was measured and a sample of 50 ml was collected and stored at − 24 °C prior to analysis. The amount of rainfall was determined using data from a rain gauge located near the roof (see the "Meteorological data" section). We calculated the proportion of influx water retained per box and per year as follows:

$$Runoff \quad abatement = 1 - \frac{[Average \quad water \quad leached\,\mathrm{per\,box\,(mm)}]}{[Average \quad rain\,\mathrm{per\,box\,(mm)}]}$$

In our case, the plants were also watered, but we did not take into account the amount of irrigation water to calculate the runoff abatement, because the ecosystem service of interest is the retention of rainfall. It should be noted that all units received the same amount of irrigation water.

Concentrations of dissolved organic and inorganic carbon were determined using an elemental approach. N-NH_4^+ and N-NO_3^- were analyzed by colorimetry on a continuous flow (Skalar Analytical, Breda, the Netherlands). DOC was measured with a total organic carbon analyzer (Shimadzu TOC-5000/5000A and TOC 5050/5050A) using catalytically aided combustion oxidation for TC and a pre-acidification for IC. Our samples were filtered at 70 μm, which implies that the dissolved organic and inorganic carbon analyzed correspond to particulate, colloids, and dissolved matter. We then calculated the average annual concentration of dissolved organic and inorganic carbon, NO_3, and NH_4 in the water as follows:

$$[Y] = \frac{x_1 \times v_{x1} + x_2 \times v_{x2} + x_3 \times v_{x3} \ldots}{V_{total}}$$

where x_i is the concentration in the overflow during event i in milligram per liter, V_i is the volume of water leachate during this event in liters, V_{total} is the sum of volumes from all leaching events in liters, and $[Y]$ is the weighted average concentration of element Y per year in milligram per liter.

2.3.3 Urban waste regulation

We calculated the consumption of organic waste over the 2 years of the study, i.e., the volume initially placed in the units plus the volume used to refill the boxes at the beginning of the second year (see above). At the beginning of the second cropping season, the Technosol heights were measured by making 12 replicate measurements every 10 cm along one 110-cm diagonal of each box using a wooden stick.

Table 2 Values for the different ecosystem services derived from the literature and the T4P experiment (a and b). Studies: (1) Technosol productive rooftops, this study and published studies (a, b, c); (2) cropland, average worldwide values; (3) asphalt roof; (4) non-productive intensive rooftop; and (5) non-productive extensive rooftop. The T4P values are expressed as averages over the 2 years of the study. Results for food supply (food production and food quality) are detailed by production and in total (lettuce, tomato, and green manure). Dry bulk density used: green waste compost = 0.3 g cm^{-3}; potting soil = 0.52 g cm^{-3}; and crushed wood = 0.18 g cm^{-3}. *Cu*, copper; *Zn*, zinc; *Cd*, cadmium; *Pb*, lead; *T.*, treatment; *TOC*, total organic carbon, *TIC*, total inorganic carbon; *TC*, total carbon

(a)

Type	T.	Vegetable	Food supply Food production (kg m^{-2} $year^{-1}$)	Food quality Pb (mg kg^{-1})	Cd (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})	Urban waste valorization Compost + potting soil (l m^{-2} 2 $years^{-1}$)	Crushed wood (l m^{-2} 2 $years^{-1}$)	Utilized waste (kg m^{-2} 2 $years^{-1}$)	(kg OC m^{-2} 2 $years^{-1}$)
1	C	Total	4.5 ± 0.4					392	–	204	53
		Lettuce	1.2 ± 1	0.035 ± 0.005	0.006 ± 0	0.37 ± 0.07	4.15 ± 0.02				
		Tomatoes	2.9 ± 2.1	0.018 ± 0.002	0.003 ± 0	1.07 ± 0.02	4.29 ± 0				
	L	Total	4.4 ± 0.9					259	150	105	30
		Lettuce	1.5 ± 0.4	0.027 ± 0.002	0.005 ± 0	0.25 ± 0.01	2.79 ± 0.05				
		Tomatoes	2.1 ± 0.4	0.026 ± 0.002	0.0015 ± 0	1.15 ± 0.07	3.39 ± 0.07				
	L-I	Total	6.1 ± 0.2					301	150	117	33
		Lettuce	2.8 ± 1.9	0.02 ± 0	0.004 ± 0	0.21 ± 0.01	2.47 ± 0.02				
		Tomatoes	2.8 ± 0.9	0.01 ± 0	0.0014 ± 0	1.07 ± 0.02	3.38 ± 0.05				
	–		6.1^{a}					–	–	–	–
	–		18.9^{c}					–	–	–	–
2	–		$10\text{-}14^{g}$					–	–	30^{f}	7
5	–		–					–	–	–	8^{i}
5	–		–					–	–	–	$3\text{ - }10^{j}$

(b)

Type	Treatment	Vegetable	Water flow regulation Rainfall retention rate (%)	Leached NO_3^- (mg l^{-1})	(kg ha^{-1} 2 $year^{-1}$)	Leached NH^+_4 (mg l^{-1})	(kg ha^{-1} 2 $year^{-1}$)	N min balance in 2 years (g m^{-2})	TOC (mg l^{-1})	TIC (mg l^{-1})	TC balance in 2 years (kg ha^{-1})
1	C	Total	84 ± 16	183 ± 89	345 ± 176	0.6 ± 0.2	1.3 ± 0.2	7	210 ± 47	9 ± 2	465 ± 154
	L	Total	74 ± 7	9 ± 3	31 ± 7	0.4 ± 0	1.5 ± 0.1	−18	313 ± 44	21 ± 5	1131 ± 82
	L-I	Total	81 ± 8	7 ± 2	17 ± 4	0.6 ± 0.1	1.5 ± 0	−19	431 ± 55	15 ± 1	1154 ± 227
	–		–	5^{b}	33^{b}	0.1^{b}	0.4^{b}		–	–	–
2	–		–	$0\text{–}75^{b}$	$0\text{–}57^{b}$	$0\text{–}81^{b}$	$0\text{–}16^{b}$		–	–	–
3	–		4^{e}	$5 \pm 3.^{e}$	–	2.6 ± 1.4^{e}	–		16 ± 15^{e}	–	–
4	–		77^{e}	54 ± 36^{e}	–	1.3 ± 0.6^{e}	–		60 ± 50^{e}	–	–
	–		$65\text{–}85^{d}$	1^{d}	–	0.2^{d}	–		–	–	–
4 and 5	–		$65\text{–}85^{b}$	$0\text{–}70^{b}$	$0\text{–}188^{b}$	$0\text{–}0.1^{b}$	$0\text{–}34^{b}$		–	–	–
5	–		$27\text{–}81^{d}$	0.3^{d}	–	0.1^{d}	–		–	–	–
5	–		13^{h}	18^{h}	–	–	–		79^{h}	13^{h}	–

[a] Samangooei et al. 2016
[b] Whittinghill et al. 2016
[c] Orsini et al. 2014
[d] Czemiel Berndtsson 2010
[e] Zhang et al. 2015
[f] References from professional producer
[g] ITAB 2017
[h] Beck et al. 2011
[i] Getter et al. 2009

2.3.4 Ecosystem service references and expression

One possible approach when evaluating ecosystem services is to compare the value of the indicator to a reference, be it another ecosystem or another management approach to the same one (e.g., Van Wijnen et al. (2011)). Because our objective was to evaluate the provision of ecosystem services using a new management option (productive rooftops with Technosols made of organic waste), we chose three types of reference: two standard rooftop management references involving asphalt and non-productive green roofs, and one standard production system, i.e., vegetable production on farmland. We searched the literature for available data on the selected indicators for these reference cases.

To express the value of the ecosystem services, we used the indicator value per square meter of productive unit, which neglects in the first instance the contribution of the bare rooftop bands between or around the productive units (Table 1).

2.4 Statistical analysis

Statistical analyses were performed using R software (R-3.1.1). The three treatments with three replicates for each case were compared using an analysis of variance after ensuring the normality of the data using a Shapiro test. A multiple comparison of means was determined by the post hoc Tukey test. Where the normality of the data was not respected, a Kruskal-Wallis test was applied followed by a post hoc Nemenyi test. A significance level of p value < 0.05 was used for each test.

3 Results and discussion

3.1 Food supply

3.1.1 Food production

Yields ranged from 4.4 to 6.1 kg m^{-2} (Table 2), with no significant differences observed among treatments. Statistical differences only emerged when considering cropped species separately (Table 2—detailed for tomatoes and lettuce). Indeed, a positive effect of earthworms (L-I) was observed for tomatoes and lettuces ($p < 0.02$), while the control produced a lower yield of lettuces than L-I ($p < 0.0007$). Conversely, L produced fewer tomatoes than L-I or C ($p < 0.001$).

Surprisingly, we obtained much lower yields per square meter than those previously observed in a similar cropping system (Grard et al. 2015). One possible explanation was an attack of fungi (mostly mildew) on tomatoes during our second growing season. We chose to use only biological pest control methods as required in organic farming, and mostly, we used preventive measures such as the application of horsetail manure, but these were not very efficient. Therefore, the fungi lasted as long as the tomato plants, thus weakening them. Nevertheless, yields for L and L-I units were equivalent to those observed in private vegetable gardens in the Paris area (Pourias et al. 2015) and other productive rooftops (Samangooei et al. 2016), but lower than those observed in a comparable rooftop system where compost was used together with mineral fertilizers under a different climate (Orsini et al. 2014) (Table 2). The present Technosols had a priori favorable characteristics for vegetable growth with a slightly acidic to slightly basic pH (Fig. 3) and low dry bulk densities (0.2 ± 0.1, 0.5, and 0.17 ± 0.03 g cm^{-3} for green waste compost, potting soil, and crushed wood).

3.1.2 Food quality

Concerns about contamination by trace metals of edible crops from urban agriculture have previously been raised because of their exposure to contaminants through different pathways of contamination (soil, air, and water; Säumel et al. (2012)). A few authors have pointed to (i) the impact of highway or industrial runoff concerning the deposition of heavy metals (Vittori Antisari et al. 2015), (ii) the fact that many urban soils are polluted with respect to soil/plant transfer (Säumel et al. 2012), and the possible advantages of growing food on an urban rooftop because some pollutants show a reduction in concentration with height (Tong et al. 2016). In our case, Pb and Cd concentrations in lettuce and tomatoes were below European limits (EU2009), while there is no EU threshold for Zn and Cu (Table 2). These results confirm our previous findings (Grard et al. 2015). Lettuce exhibited higher trace metal concentrations than tomatoes for all elements except copper (Table 2) ($p < 0.05$) in accordance with other studies (Murray et al. 2009). The soil type (reflecting the treatment used in our case) also affected the trace metal concentration (Table 2) depending on the type of crop and the trace metal element ($p < 0.05$). Vegetables grown on potting soil showed higher concentrations of trace elements (all trace metal elements for lettuce, copper, and zinc for tomatoes) despite a lower concentration (see below) in the substrate, but more favorable soil parameters for transfer such as a lower pH (Fig. 3). The higher concentrations for L than L-I appear significant ($p < 0.05$) for all elements except copper in lettuce. As for the Technosols, the compost of green waste contained 40.13 ± 1.33 mg kg^{-1} Cu, 0.47 ± 0.07 mg kg^{-1} Cd, 51.60 ± 5.57 mg kg^{-1} Pb, and 179.33 ± 6.66 mg kg^{-1} Zn. The potting soil contained 13.77 ± 3.81 mg kg^{-1} Cu, 0.16 ± 0.03 mg kg^{-1} Cd, 16.07 ± 0.15 mg kg^{-1} Pb, and 66.33 ± 1.05 mg kg^{-1} Zn. The crushed wood contained 7.2 ± 1.5 mg kg^{-1} Cu, 0.1 ± 0 mg kg^{-1} Cd, 7.4 ± 1.9 mg kg^{-1} Pb, and 32.3 ± 5.1 mg kg^{-1} Zn. All these values were well below the existing French norms for a growing medium (NF U 44-551), which may explain the relatively low trace element contents of the vegetables. Trace element concentrations may have two origins: aerial deposition and transfer from the Technosol. The vegetables were washed with water, the rooftop is on a five-story building, and no major highway is located within 1 km of the site, which limits aerial deposition (Tong et al. 2016; Vittori Antisari et al. 2015). However, other pollutants, such as PAH, should also be investigated.

3.2 Mitigation of runoff water

Most of the rainfall was retained by the cropping units (Table 2). C, L, and L-I exhibited rainfall retention rates of 84, 74, and 81%, respectively. The only significant differences were between C and L, with the former having the higher retention capacity ($p < 0.0002$). Retention is associated with several processes, including the absorption of water by plants, evapotranspiration, and retention by the Technosols. Both compost and potting soil are likely to exhibit a high water retention capacity.

In fact, the mitigation of runoff by the Technosols in our case is even higher than reported because we did not account for the irrigation water (which would result in retention rates of 90% for C, 84% for L, and 88% for L-I per unit of surface area). If retention rates are expressed not at the scale of the production unit but at the scale of the rooftop, i.e., accounting for the paved alleys between production units as 20% of the roof surface, the retention rates then lie between 59 and 67%.

Many authors have investigated the mitigation of runoff by green roofs (Table 2), indicating a high variability among green roof systems. Extensive green roofs retain between 27 and 81% of rainfall while intensive rooftops retain between 65 and 85% (Czemiel Berndtsson 2010). This variability reflects the diversity of existing systems as well as the influence of a number of variables including climate, slope, type of Technosol, and age.

3.3 Water quality

3.3.1 Mineral nitrogen loss

The three Technosol units leached between 16.7 and 345.3 kg ha^{-1} of mineral nitrogen over 2 years (Table 2). Most mineral nitrogen losses occurred in the first month of the experiment: 97% of total losses for C, 77% for L, and 57% for L-I. Mineral nitrogen losses were overwhelmingly in the form of nitrate (e.g., 90% by mass for L-I). The control units leached most nitrates in terms of the weighted average concentrations (183.2 mg l^{-1}) and leached mass, the latter being 16 times higher in C than that in the L and L-I compost units. The L unit leached significantly more nitrate than L-I, suggesting the positive effect of earthworm inoculation. In terms of European standards for nitrate concentrations in potable water [< 50 mg l^{-1}], L, L-I, and C exceeded this value in 3, 1, and 4 leaching events, respectively, out of a total of 40, 34, and 39 leaching events over the 2 years of the study. This nitrogen loss is ascribed to the biodegradation of the compost and potting soil, given that the initial concentrations of nitrate in the compost and potting soil are insignificant.

The L and L-I experimental units exhibited an equivalent or slightly higher loss of nitrate and ammonium per year by mass compared with cropland, and non-productive and productive rooftops (Table 2) (Whittinghill et al. 2016; Zhang et al. 2015). In the L and L-I units, the amount of nitrate leaching and average nitrate concentrations were similar to those found in the only productive farm investigated to date (Brooklyn Grange) despite the very different contents of organic matter: more than 50% in our experiment compared with 10% at Brooklyn Grange (Whittinghill et al. 2016). The higher losses of nitrate in the latter case could be due to (i) the use of mineral fertilizers, (ii) the climate, and (iii) the vegetation cover (type and intensity).

3.3.2 Carbon loss

Unlike nitrate leaching, we observed a constant loss of carbon over time, mostly in the form of dissolved organic carbon (more than 92% of the loss for all units), with the remainder being small particles of organic matter. Major differences were observed among units, with the order of the average concentration of dissolved organic carbon being C < L < L-I (Table 2). We assumed that the losses of dissolved organic carbon were due to the initial concentrations of dissolved organic carbon in the compost and potting soil and a rapid biodegradation of the compost, especially in the presence of earthworms (L-I).

Our constructed Technosols exhibited greater carbon losses through leaching than those described in the few references available in the literature on green roofs (Czemiel Berndtsson 2010; Whittinghill et al. 2016; Zhang et al. 2015) (Table 2). Our productive green roof with a rich organic-based substrate thus degraded the quality of the runoff water significantly more than extensive green roof systems (Beck et al. 2011).

3.4 Waste valuation and carbon storage

The amount of waste valorized depends on the initial quantity of substrate used to construct the Technosols and the amount used to refill them after 1 and 2 years of cropping. The contrasting bulk densities of the materials (compost, crushed wood, and potting soil) and their rapid rearrangement after setting the units explained the differences in the volume used to set the systems per square meter. After one growing season, the L-I units showed the largest shrinkage, i.e., 50% reduction in the height of the Technosols compared to 36% for L and 31% for C. After the second growing season, this proportion reduced to 30% for L-I, 33% for L, and 14% for C, which was significantly less than in the first year ($p < 0.016$). Over the 2 years, a higher proportion of substrate shrinkage was observed for L and L-I ($p < 7.2 \times 10^{-8}$; data not shown) and a larger amount of organic waste was then used to refill the unit (Table 2). The measured shrinkage could be due to two processes: particle rearrangement with a subsequent compaction of material as observed in the first weeks after setting the units, and biodegradation of the organic materials. Treatment with earthworms (L-I) resulted in the most shrinkage during the first year ($p < 0.00014$), suggesting the possible impact of earthworms on both processes, as described for natural soils.

High levels of Technosol shrinkage, as observed here, are often considered as a sign of unsuitable growing substrate. However, in our case, the yields suggest that the physical conditions remained favorable for root growth in line with the low bulk densities. Furthermore, both the biodegradation of organic materials and the refilling of the units after 1 year provided nutrients to the plants.

To our knowledge, this service has not been evaluated for other productive green roofs, and our system valorizes urban wastes much more highly than extensive rooftops (Table 2). Because green roof Technosols are carbon-rich materials, they can be seen as a means of storing carbon. The constructed Technosols exhibited high inputs and potential stocks of organic carbon compared to standard extensive green roofs (Table 2). However, in order to assess the role of Technosols in storing organic carbon as a means of mitigating CO_2 emissions, there is a need to know the residence time of the carbon and compare it to those of alternative fates of compost, potting soil, and wood waste (e.g., combustion, application to cropland) in order to estimate the carbon balance of such green infrastructures. In other cases, it has been shown that carbon emissions linked to green roof implementation (e.g., fuel consumption) could be compensated by carbon storage and sequestration in less than 9 years (Getter et al. 2009).

3.5 Provision of ecosystem services by productive rooftops

A sustainable and productive green roof should produce high-quality fresh vegetables for several years, avoid the use of non-renewable resources such as top soil and peat, provide an opportunity for recycling of urban organic waste, and deliver other ecosystem services such as reducing runoff from roofs without altering the water quality. Because so few vegetable production systems have been designed to date using only urban organic waste or recycled materials as observed by Molineux et al. (2009), the valuation of the ecosystem services of such cropping systems is useful.

The ecosystem services considered herein are provided by two components of the production units, notably the Technosols and the plants, which for example influence runoff quantity and quality through the absorption of water and nutrients, and evapotranspiration. We focus on Technosols because they have received less attention to date. We found that a compost-based Technosol provides quite similar or even improved ecosystem services compared to potting soil. Indeed, yields began to decrease in the second year for the potting soil, presumably because of nutrient exhaustion as confirmed by the very small quantity of mineral nitrogen leaching from these Technosols in the second year. Compost-based Technosols were, however, less favorable in terms of carbon leaching. Productive units with potting soil appeared less sustainable than those with compost-based ones, because of the addition of synthetic fertilizers to the peat during the manufacture of the potting soil, and the high environmental impact associated with peat extraction. Earthworm inoculation barely influenced the evolution and ecosystem services of the Technosols, apart from lower levels of substrate shrinkage and nitrate leaching.

We demonstrate that compost-based Technosols generate “new” ecosystem services (food production and an increase in the value of waste) compared to “standard” extensive green roofs, while ensuring important runoff mitigation. However, they also generate ecosystem disservices, with the leaching of nitrates and soluble carbon, which decreases the runoff water quality. As for green roofs in general, one of the main research questions about productive rooftops relates to an understanding of whether they are a sink or a source of chemical substances. Berndtsson et al. (2009) show that both intensive and extensive green roofs can act as a nitrogen sink (despite the nitrogen dynamics in the substrate). We demonstrate here that a productive rooftop based on organic waste acted as a sink of mineral nitrogen (i.e., output of mineral nitrogen < input of mineral nitrogen, see Table 2), whereas it acted as a source of dissolved carbon. A crucial aspect in the conception of organic waste-based Technosols for food production is then the identification of the best trade-off between the expected mineralization of the organic waste to provide nutrients to plants and a limited mineralization to restrict the leaching of nitrogen, carbon, or other elements.

To develop sustainable productive rooftops with a broader range of ecosystem services than those provided by standard green roofs, there is a future research need to investigate the possible trade-offs in Technosol compositions with regard to the provision of ecosystem services over time, especially Technosol evolution. Possible deterioration in water quality should be studied regarding the specific Technosol composition requirement for productive roofs (i.e., a high proportion of organic matter). Finally, the use of biowaste compost produced by local compost units should be investigated.

A number of other potential ecosystem services were not investigated, namely biodiversity support, the regulation of pollination, climate regulation, and cultural services. As urban agriculture continues to be an increasing trend in many cities around the world, other ecosystem services need to be evaluated in order to allow a more comprehensive assessment to be made.

4 Conclusions

We have presented the first quantitative assessment of ecosystem services provided by productive rooftops. We find that making rooftops productive using organic waste has the potential to generate many urban ecosystem services, though with some potential disservices: the result is high levels of food provision with acceptable food quality in terms of contaminants, important runoff mitigation, and use of a local organic waste, but with a negative effect on runoff water quality in terms of carbon. We also showed that the challenge for researchers on the conception of constructed Technosols made of urban wastes is to manage the trade-offs between desired and unwanted mineralization of organic materials.

The ecosystem services approach allows for a comprehensive (of several ecosystem services) yet synthetic (one or just a few indicators per service) comparison between different management options for rooftops. The ecosystem services approach thus appears useful for city planners in the design of green infrastructure and for designing sustainable urban agriculture systems and more generally for conceiving cities with high levels of ecosystem services.

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