# Recycling urban waste as possible use for rooftop vegetable garden

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**Key words**

urban farming, urban agriculture, organic waste, green roof, vegetables.

**Abstract**

Urban authorities in Europe are confronted with increasing demands by urban dwellers for allotment gardens, but vacant urban soil tends to be scarce and/or polluted by past industrial activities. A possible solution for local authorities could therefore be to promote rooftop gardening. However little technical information exists on certain forms of rooftop urban agriculture, called Z-Farming. In 2012, a pilot experiment was run in Paris (France). Simple and cheap systems of rooftop gardening were tested on a rooftop using as crop substrates only local urban organic waste so as to contribute to the urban metabolism. Production levels and heavy metal contents in cropping substrates and edible vegetables were measured. Available results show (i) high levels of crop production with limited inputs compared to land professional gardening, (ii) low levels of heavy metal pollutants in the edible parts of the crops, especially for Cd and Pb with respect to EU norms for vegetables and (iii) positive influence on yields on organizing the substrate in layers and enhancing the biological activity through earthworm inoculation. These encouraging results allow us to consider that rooftop gardening is feasible and seem to have a great potential to improve urban resiliency. It will nevertheless be necessary to identify more precisely the types of roof that can be used and to assess more fully the generic result of the low level of pollution, as well as the global sustainability of these cropping systems.

## Introduction

Urban sprawl increase and development across the globe are producing many challenges including atmospheric, soil (Säumel et al., 2012; Alloway, 2004; Wong, Li, & Thornton, 2006) and water pollution due to the concentration of people in urban areas (Girardet, 2008), needing transport for food production and supply. Among these challenges urban authorities and inhabitants are increasingly concerned about the food security of cities, for example like Toronto, Cleveland and Detroit.

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**Figure 1** : The rooftop of AgroParisTech in 2012. On the right side the first crop sequence (S1) and on the left side the second crop sequence (S2) (Photo credit: Xavier Remongin)

(MacRae, Gallant, & Patel, 2010)(Grewal & Grewal, 2012)(Aubry, Dabat, & Mawois, 2010)(Aubry, 2013).

Partially in response to this growing concern, the phenomenon of urban agriculture has been spread worldwide, especially in the northern hemisphere, for more than a decade. Urban agriculture can be defined as an agriculture located inside or near the city, producing mainly for the city and using resources shared and/or in competition with urban uses (Smith, Moustier, & Mougeot, 2004; Veenhuizen, 2006). Urban agriculture is characterized by its multi-functionality and diversity of forms (Aubry, 2013)(Smit, Ratta, & Nasr, 1996; Pourias, 2013). Amid these forms, urban allotment gardens have been developed rapidly worldwide in the last few decades. For instance, a city like Paris has seen the number of urban allotment gardens rise from 5 in 2002 to more than 100 in 2014 (Pourias, 2013 op.cit). This strong development coupled with the need for space in megacities led to many unsatisfied demands and waiting lists for urban dwellers applying for an urban allotment garden. The exploitation of unused spaces such as rooftops can be a solution to this scarcity of space for urban allotment gardens. This solution is already used by urban agriculture, mainly for commercial purposes in cities like Montreal, Toronto or New York (Specht et al., 2013)(Thomaier et al., 2014). In Paris, the newly elected mayor Anne Hidalgo promised during the 2014 election campaign to turn 100 ha of Parisian walls and rooftops into green roofs and walls, 30% of this area will be dedicated to gardens or food production (Hidalgo, 2014). A study by the Urban Parisian Planning Study (APUR, 2013) investigated the current area of rooftops that could be turned into productive rooftops inside the city. These eligible rooftops were identified by the way of aerial photography cross-compared with building licenses and specific criteria (minimum area of 200m2, slope below 2% and a supposed concrete structure). The results showed 460ha of flat roofs, among which 80ha were classified as having a "high potential for vegetalization". Further case by case investigations are needed to assess such classification. Anyway, this study provides a first survey of the actual potential of Paris' rooftop gardening. Note that (i) Paris is well known for its old centre that presents a very low rate of eligible rooftops, as shown in the APUR study. (ii) The potential of the suburbs of Paris (which represent the majority of the region's urban surface area) has not yet been investigated, although these areas are likely to have a higher potential, owing to their more recent, flat rooftops. This emergence of new forms of urban agriculture in or on buildings is called "Z-farming" for Zero-Acreage Farming – a term coined by Specht and Thomaier (Specht et al., 2013; Thomaier et al., 2014). Z-farming is raising research questions especially on the technical aspects of setting up rooftop gardening. Concerning the choice of a growing media, many researchers worked for more than a decade in horticulture and soil science on the use of waste as a growing substrate or peat/soil substitute (Ostos, López-Garrido, Murillo, & López, 2008; Abad, Noguera, & Burés, 2001; Hernández-Apaolaza, Gascó, Gascó, & Guerrero, 2005; Rokia, Séré, Schwartz, & Deeb, 2014; Morel, Poncet, & Rivière, 2000). In the

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research reported here, we sought to open a new pathway as we consider the urban environment as a source of possible organic and mineral growing substrate using only local urban waste for a productive rooftop. This led us to design an experiment with rooftop gardening in Paris that take into account the specific constraints of this environment. We adopted three main principles for the pilot experiment:

1. To be transposable to people without specific agricultural skills and with limited economic resources. This implied to look for cheap and easy ways to cultivate. These conditions, as well as the minimization of the workload and our environmental friendly approach (see below) excluded the use of high-tech production techniques (such as hydroponic systems or rooftop greenhouses).
2. To be based on the use of local urban organic waste as a part of the urban metabolism (Barles, 2009). This could have many direct advantages such as, avoiding the costs and harmful greenhouse gases generated through waste transportation and treatment and recycling the nutrients at a local scale thus partly turning the city into a closed loop system (Smit & Nasr, 1992). Furthermore, using organic waste as a cultivation substrate is an advantage in these cultivation conditions, as it is a lightweight substrate.
3. Not to use any chemical fertilizer nor any pesticide or insecticide, in order to limit contamination of food products and ecosystem as well as to limit the use of energy costly fertilizer. In any case local regulations in a city like Paris and a future law has or will prohibit the use of chemical products for green spaces. Exogenous substrates like peat or coco fibre are used for some rooftop production in Montreal or New York. However due to their environmental impacts (Cleary, Roulet, & Moore, 2005) we chose not to use them in our experiment. Our environmentally friendly approach also imply that a key aspect of our cropping system would be the substrate's sustainability (i.e. its capacity to ensure a significant amount of production before needing to be replaced).

The overall purpose of this paper is to assess the potential of such cropping systems, based on the first results of a pilot experiment in which we manipulated the nature of the substrate components, their organization in production beds and the presence of soil organisms. We focus here on the production level of our cropping systems and on a key aspect of UA: the content of pollutants in edible production.

## Materials & Methods

### Rooftop experiment

The experiment T4P (Pilot Project of Parisian Productive Rooftops) was started in 2012 on the rooftop of AgroParisTech (French Technical University of Agronomy; 16 rue Claude Bernard, 75 005; coordinates: 48°50'24.4"N, 2°20'54.5"E). We chose to use wooden containers classically used as a backyard composter. This choice was made not only to facilitate the experimental observations and measurements but also with the idea that small spatial units could be easier to manage than plots on a roof. These containers are very easy to build and are sold cheaply in garden centres (around 20€ for a wooden container 40 cm height). They also allow an urban allotment gardens to be more flexible by adapting the total numbers and spatial localization of cropping containers on the roof to its specific characteristics (global weight carrying capacity and variability on the roof, useable area, number of families each year, etc.). A picture of the experiment is shown in Figure 1.

### Growing media

#### Initial substrates:

We used three types of urban organic waste as a component of the growing substrate:

- Green waste compost from urban public parks and green spaces, which is commonly made in Paris as well as in the suburbs. This compost is used by the public parks services of the city in their green space as the compost maturity turn it into a good fertilizer. The surpluses are frequently given to individuals or local non-profit organizations. Our supplier is a company located in Versailles near Paris, BioYvelinesServices (see annex 1 for the description of our experiment partner);
- Crushed Wood, also from public spaces, of which the surpluses are given or sold cheaply

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to the public. An ample supply was provided by BioYvelinesServices;
- Coffee grounds with Pleurotus Ostreatus mycelium was a more original substrate: it came from a new urban farm (The U-Farm, part of the UpCycle company ; see annex 1) producing mushrooms in ship containers on a coffee grounds mixed with wood chips. U-Farm, in partnership with a leading coffee supplier, collect used coffee through a specific supply chain from coffee machines in Paris.

We used a potting soil (see annex 2 for the detailed composition) as a control. This horticultural substrate, commonly used in urban allotment gardens, was supplied by a garden centre. Woodchips were also used as mulch in each box, in order to minimize substrate evaporation and weeds. The main agronomic characteristics of our substrates are presented in Table 1.

**Mixes tested:**

Our cultivation system was inspired by an original gardening practice born in the United States of America and which started to be known and used in France a few years ago: lasagne beds (Collaert, 2010). The idea is to mimic a soil by putting down layers of "brown" and "green" organic matter. The "colour" relates to the decomposability and mineralization rate. For instance, a brown layer could be crushed wood that is supposed to have a low rate of mineralization and provides an input of carbon, with a high C/N ratio. The green layer could be a green waste compost with a high mineralization rate and a consequent input of nutrients due to a low C/N ratio. Every year, at the beginning of the cropping season, an additional layer of "green" matter is added. This ensures an input of organic matter to provide nutrients by mineralization to compensate for that used by the previous crop. Inputs of chemical or organic fertilizer during the cropping season can thus be avoided.

We tested the nature of the initial substrate used and its distribution in the container, either as a lasagne or homogenously mixed, and the inoculation with earthworms. The latter were introduced with the hypothesis that earthworms would create and maintain a soil structure favourable to plant growth. Two functional groups were used (epigeic and anecic) given their contrasted roles in soil (Blouin et al., 2013)(van Groenigen et al., 2014). Five mixtures of the three organic wastes and a potting soil were randomly distributed in 2*15 wooden boxes of 0.64m2 each, with 0.5 m between them. The five treatments are presented in Figure 2 and composed as follows:

- Treatment n°1 (T1): two layers of 15 cm of green waste compost and crushed wood.
- Treatment n°2 (T2): two layers of 15 cm of green waste compost and crushed wood in which we inoculated three species of earthworms corresponding to two functional groups (epigeic and anecic): 15 Dendrobaena Veneta (epigeic earthworm) adults, 35 Eisenia Fetida (epigeic earthworm) adults and 10 Lumbricus Terrestris (anecic earthworm) adults.
- Treatment n°3 (T3) : three layers : two of 12.5 cm composed of crushed wood and green waste compost and 5 cm of coffee ground with Pleurotus Ostreatus mycelium.
- Treatment n°4 (T4): 30 cm of a green waste compost and crushed wood mixture (50/50 v/v).
- Control (C): 30 cm of potting soil.

Each box was filled at the bottom by 5cm of clay balls used as a water reserve and surrounded by an EPDM (Ethylene-Propylene-Diene Monomer) membrane. On the top of this we placed 30cm of growing substrate surrounded by a "geotextile" through which the roots can grow.

**Cropping species:**

Each row of 15 boxes corresponded to a crop sequence: either lettuce (Lactuca sativa) then cherry tomatoes (Lycopersicum esculentum var. chery) then green manures (Trifolium incarnatum and Secale cereale) called S1; or cherry tomatoes then lettuce then green manures called S2. These two sequences were designed to represent the most common crops grown in UAG in Paris As well as to vary by their nutrients needs over the cropping season. Indeed, the tomatoes plants export more nutrients to grow than the lettuce (Argouarc'h, 2005). In this paper we focus on the first sequence, (S1), as shown in Figure 3.

**Technical processes of the experiment:**

The only input allowed was organic, applied at the beginning of the cropping season (end of


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**Table 1**: Average physico-chemical characteristics of the source materials for growing substrate used in 2014. SD = Standard Deviation and DM = Dry matter, n=3. The analyses were performed by the soil laboratory of INRA ARRAS that is accredited by COFRAC. http://www6.lille.inra.fr/las

| | pH water (mean ± SD) | $CaCO_3$ total (mean ± SD) g/kg of DM | Organic carbon (mean ± SD) g/kg of DM | Total nitrogen (mean ± SD) g/kg of DM | $C_{organic}/N_{total}$ (mean ± SD) | Potassium (mean ± SD) g/kg of DM |
|---|---|---|---|---|---|---|
| **Green waste compost** | 7.7 ± 0.03 | 53.2 ± 1.6 | 233.0 ± 31.1 | 11.8 ± 0.2 | 19.6 ± 2.6 | 1.2 ± 0.04 |
| **Coffee ground with mycelium** | 6.0 ± 0.8 | 11.1 ± 9.4 | 436.3 ± 5.1 | 26.7 ± 1.3 | 16.4 ± 0.6 | 0.4 ± 0.09 |
| **Crushed wood** | 7.3 ± 0.07 | 3.2 ± 1.08 | 454.3 ± 5.7 | 4.7 ± 0.3 | 96.9 ± 6.8 | 0.6 ± 0.01 |
| **Woodchips** | 6.9 ± 0.04 | <1 ± <0.01 | 484.7 ± 4.7 | 1.5 ± 0.2 | 325.8 ± 28.6 | 0.2 ± 0.04 |
| **Potting soil** | 6.7 ± 0.06 | 18.6 ± 7.9 | 264.0 ± 2.7 | 6.8 ± 0.1 | 39.1 ± 0.2 | 1.3 ± 0.02 |

March or April) when the containers were refilled with organic material (to 30 cm height) to compensate for substrate compaction and biodegradation. In March 2013 the following proportion of the initial volume of the substrate was filled with (in % of initial volume of the substrate):

- C: 25% of potting soil
- T1: 34% of green waste compost
- T2: 40% of green waste compost
- T3: 27% of coffee ground with mycelium (16% of the 27% as the bottom layer) and green waste compost (the other percent as the top layer)
- T4: 37% of green waste compost mixed with crushed wood (50/50 v/v)

As for diseases protection, we applied copper sulphate only on the tomato plants, in three treatments in 2012 (June, July and August) and two in 2013 (June and July). In parallel we did two preventive horsetail treatments in 2013 on tomatoes and in 2013 we put one Indian carnation plant in each box to avoid aphids. The box was irrigated by way of two kinds of drip irrigation system in the cropping season 2012 and 2013.

**Sampling and analyses:**

During the harvest of lettuce (June 2012 and June 2013) and tomatoes (between July and October 2012-2013) 100g of fresh matter were collected from each box washed and dried at 40°C for at least a week. The fresh and dry matter was weighed in order to determine the precise biomass production. Five trace metals (Cd, Pb, Cu, Zn and Hg) currently found in polluted urban garden soils were analysed (Alloway, 2004)(Wong et al., 2006). A Polarized Zeeman Atomic Absorption spectrophotometer model Z5000 (HITACHI) was used by means of ETAAS (Electrothermal Atomic Absorption Spectrometry) to determine Cd, Pb and Cu and by means of FAAS (Flame Atomic Absorption Spectrometry) to determine Zn. Hg was analysed by means of CVAAS (Cold Vapor Atomic Absorption Spectrometry).

Three times a year the growing substrates were sampled layer by layer (12 or 16% of the box volume) and 500g of each layer were used for agronomic and pollutant analyses. Each substrate was dried at 40°C and sieved at 2mm by a crusher. The agronomic analysis (pH, OM, CaCO3 etc.) was performed by a certified soil laboratory. Climatic data were registered through an automatic station giving daily temperatures, rain and evapo-transpiration. Due to a technical problem at the meteorological station, the data for the two growing seasons are not yet complete (see Annex 3).

**Statistical analysis:**

Statistical analyses were performed on fresh biomass production (3 replicate boxes per treatment) using R software (R-3.1.1). The five treatments were compared through an analysis of variance (ANOVA) after ensuring normality of the data. A multiple comparison of means was determined by the 'post-hoc' Tukey test. A significance level of $P<0.05$ was used. All the p-values from the analysis are presented in Annex 4.

## Results

**Production levels**

Figure 4 (i), (ii), (iii), (iv), (v) & (vi): Biomass production (edible: tomatoes and lettuce; above ground for green manures) per box during the two-year ex-

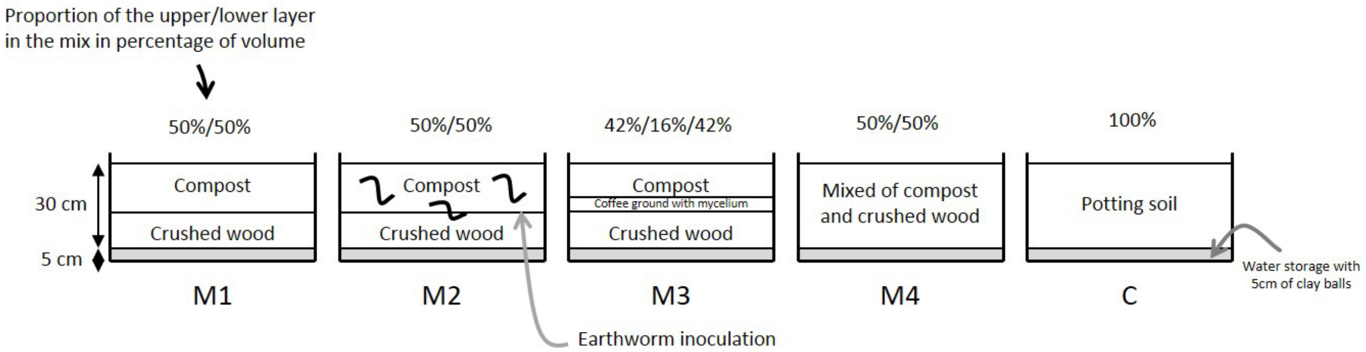


**Figure 2** : Description of the five treatments used in the T4P experiment

periment T4P. On the graph different letters means significant differences; p-value<0.05. The red dot symbolize the mean value and the red line show the standard deviation.

As Figure 4 shows, higher yields were obtained every year for treatment T2 and T3, which are the most diversified ones in terms of substrates and biological diversity. For green manure and tomatoes higher yields were observed in 2013 than in 2012, reaching 3.24 kg.box-1 of tomatoes for the T3 in average and 1.10 kg.box-1 of green manure in average for the T2. The opposite situation was noted for lettuce, with higher yields in 2012 than in 2013. The lettuces weighted more than 540g per piece for the T3 treatment.

By comparison with T2 and T3, the control did not

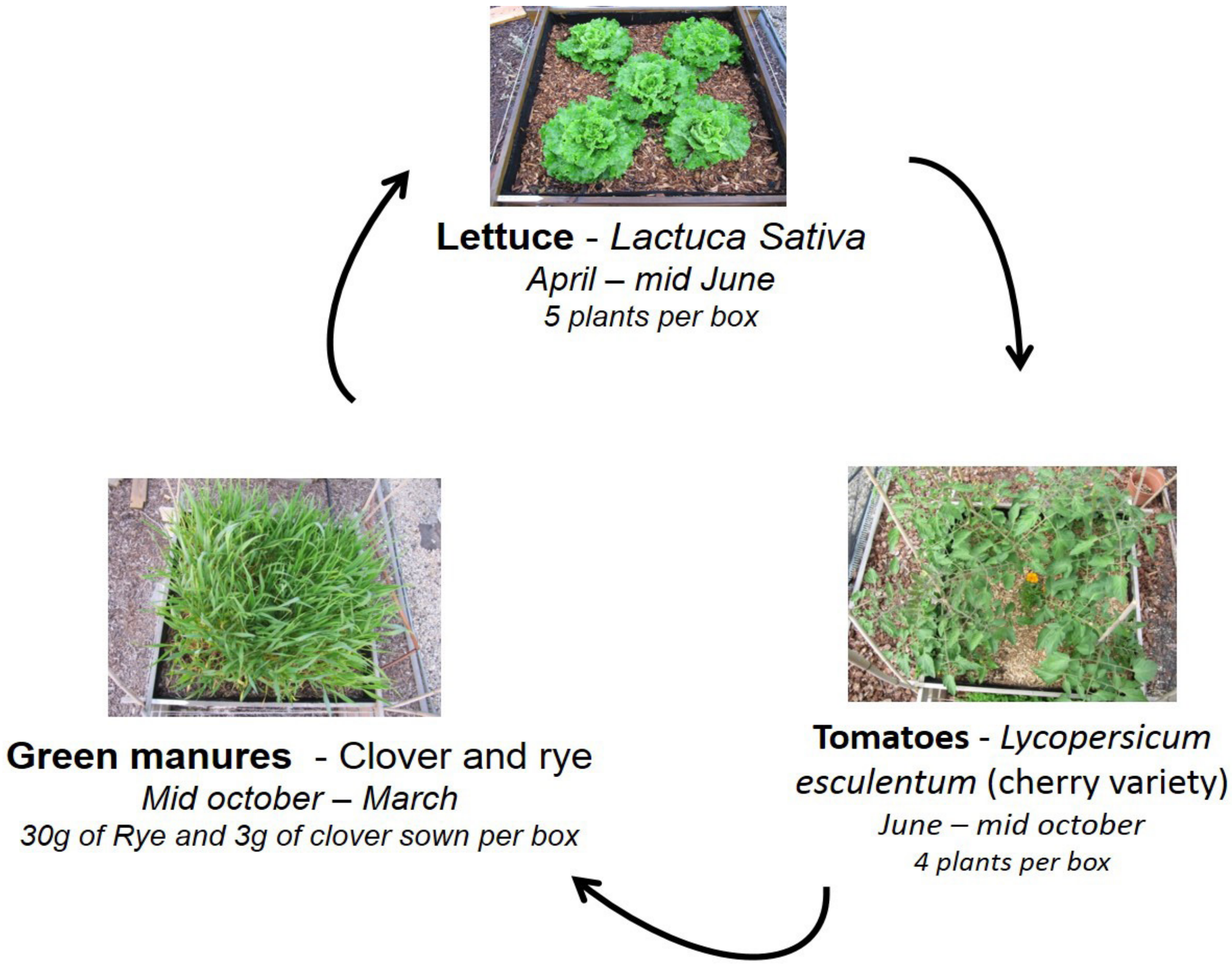


**Figure 3** : Representation of the first crop sequence (S1) in the T4P experiment

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lead to good yields. Respectively four and six out of six harvest were significantly lower for the control than for T2 and T3. This shows the interest of growing food on urban organic waste rather than potting soil. Putting the different substrates in layers instead of directly mixing them seems to have a positive effect on yield. In fact, the yields were significantly higher for the T1, T2 and T3 (in comparison with T4) respectively for 3, 4 and 5 harvest out of six.

The inoculation of earthworm seems to have either a positive or no effect on yield. For T2, the harvest was higher for only one harvest (and equal for 5th others). Remaining mycelium inoculation has as well either a positive or no effect on yields. Indeed, T3 showed higher yields than T1, for three harvest.

#### Pollutant levels

During the two seasons of the experiment we measured the concentration of five trace metals in the edible crops. Of these five elements, only Cadmium (Cd) and Lead (Pb) are regulated by a European standard that we take as a reference here. The content of Pb and Cd in lettuce (Table 2 a & b) and tomatoes was four to ten times lower than the European norms. Similar results were obtained for Cd and Pb levels in tomatoes: 0.001 to 0.003mg of Cd per kg and 0.005 to 0.02 mg of Pb per kg (fresh weight) to be compared with the EU limits 0.5 mg of Cd per kg and 0.1mg of Pb per kg (fresh weight). With the exception of treatment T1 in 2013 where the lead content was 0.11 mg.kg-1, for which we have no satisfactory explanation at the moment.

The trace metal content in our parental substrate was under the applied standard in all cases (French standard NF U 44 551 (AFNOR, 2002)). Lead and cadmium concentrations were respectively 40mg.kg-1 and 0.47mg.kg-1 in compost and 0.17mg.kg-1 in potting soil. Over the two-year experiment there was no significant change in the trace metal content in any of the substrates.

### Discussion

The difference of yields between 2012 and 2013 might be due to meteorological conditions (see Annex 3) or to differences in substrate evolution although we have no available data yet. Note that our cropping period for tomatoes was shortened in mid-October because of green manure seedling periods. It is also noteworthy that our experimental device presents a low density of lettuce compared to professional producer's practices (five lettuces for 0.64m2 against 7 to 11 for a professional producer (personal communication).

Few studies focus on an evaluation of the potential for rooftop edible food production (Whittinghill, Rowe, & Cregg, 2013; Kortright, 2001; Orsini et al., 2014) and none focus on food production using only urban organic waste. We provide a first insight of this potential. During the two growing seasons we found three major patterns:

- Food production using urban waste (T1, T2, T3 and T4 in comparison of C) is significant. Indeed, in almost all harvests the potting soil was one of the less productive as well as the T4. The fact that this potting soil offers the lowest yield may however be explained at least partially by the non-use of mineral fertilizer. A classical input in horticultural cropping systems ;
- The layout in lasagne beds has a positive effect (T4 in comparison with T1, T2 and T3) on the production, especially for T2 and T3. One hypothesis could be made to explain this lasagne effect: the high C/N ratio of the crushed wood may immobilize all the nitrogen from the compost due to the microbial activity. It should be note that the effect was stronger on yield of lettuce and green manures compared to tomatoes so the rooting system could have an impact.
- Earthworms or coffee grounds with remaining mycelium inoculation have a mixed direct effect (positive or null) on the production level (T2 and T3 in comparison with T1) and an impact on substrate evolution (i.e increase in water retention).

Our production results show the feasibility of growing food on a rooftop garden based only on local urban organic waste. Regarding the first experimental results, during the whole cropping season (April to October) and despite the limits explained above, we demonstrated good or even high levels of food, production. Thus, for T2 or T3 we produced around 4.8 to 7.5kg/m2, equivalent to 48 to 75t/ha (see Annex 6) without any fertilization other than that brought by the organic waste itself. The yields of T2

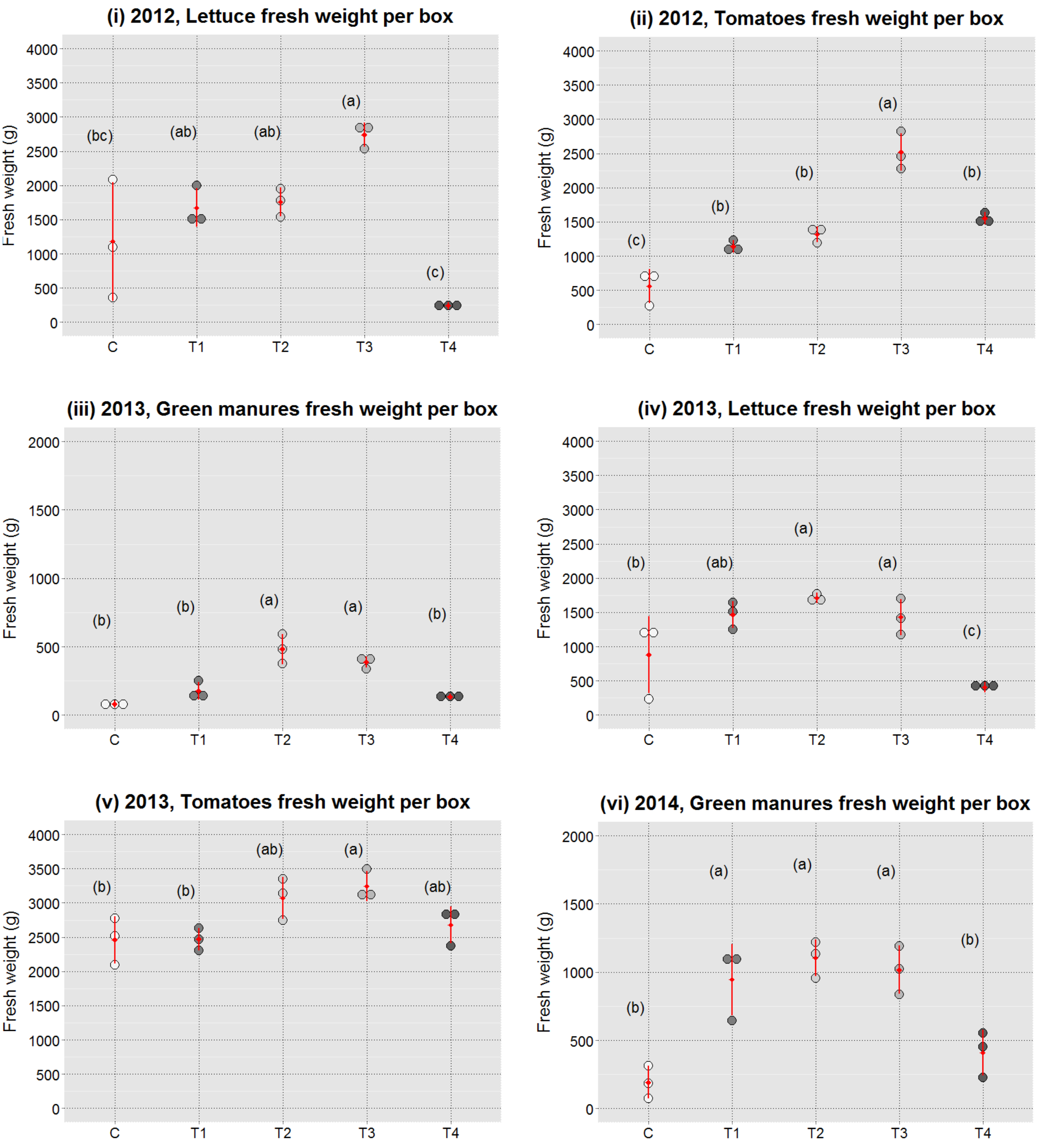


**Figure 4 (i), (ii), (iii), (iv), (v) & (vi):** Biomass production (edible: tomatoes and lettuce; above ground for green manures) per box during the two-year experiment T4P. On the graph different letters means significant differences; p-value<0.05. The red dot symbolize the mean value and the red line show the standard deviation.



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and T3 were higher than those obtained currently in "on the ground" urban allotment garden where gardeners are cultivating mainly to produce food (Pourias, 2013). This is also the case if we compare with professional open-air organic market gardens in the Parisian region: in 2012, 14 000 tons of lettuce were produced in the Parisian Region from May to October on 740 ha (i.e. with a mean yield about 20 t/ha). For tomatoes, regional data is not available but at the national level the mean yield of open air tomatoes is around 52 t.ha-1 – while tomatoes cultivated in green houses reach a mean yield of about 236 t.ha-1 (DRIAFF, 2013; Agreste, 2013)

As presented above, we observed a strong decrease of the volume of substrate (- 10 to 15 cm after the first cropping season). This could result from a physical dynamics (compaction) or a biological one (biodegradation). This evolution contrasts with the classic behaviour of a peat-based substrate supposed to be physically stable over time. And highlights the question of the sustainability of growing substrate based on local urban waste. Especially the question of the possible (physical and/or chemical and/or biological) impediment to vegetable growth.

We designed our agro-ecological cropping system as a living ecosystem in which the resilience should increase with time. In doing so we observed the importance and benefits of greater diversity of soil fauna including higher yields. During experimental tests we measured the strong development of the epigeic species of worms (data not shown here). The focus on the specific influence and importance of biological diversity will be examined in another study. But even now, these results suggest the need to study the potential of these rooftop gardens to be an habitat for urban fauna such as arthro-

**Table 2 a and b**: Cadmium and lead contents in cherry tomatoes (a) and lettuce (b) during the two-year experiment. European standard refers to the standard CE n°188-2006. FM = Fresh Matter and SD = Standard Deviation.

**a- Cherry tomatoes**

| Treatment | 2012 | | 2013 | | European Standard |
|---|---|---|---|---|---|
| | **[Cd]** ± SD mg.kg$^{-1}$ of FM | **[Pb]** ± SD mg.kg$^{-1}$ of FM | **[Cd]** ± SD mg.kg$^{-1}$ of FM | **[Pb]** ± SD mg.kg$^{-1}$ of FM | |
| C | 0.009 ± 2.6E-04 | 0.005 ± 1.5E-03 | 0.002 ± 6.0E-05 | 0.03 ± 3.0E-03 | |
| T1 | 0.002 ± 5.6E-05 | 0.008 ± 1.3E-03 | 0.003 ± 4.0E-05 | 0.1 ± 8.2E-03 | |
| T2 | 0.002 ± 7.9E-05 | 0.02 ± 8.2E-03 | 0.004 ± 2.3E-04 | 0.03 ± 2.1E-03 | **0.2** |
| T3 | 0.003 ± 1.2E-04 | 0.01 ± 1.3E-03 | 0.003 ± 9.0E-05 | 0.03 ± 4.0E-04 | |
| T4 | 0.001 ± 1.02E-04 | 0.005 ± 8.4E-04 | 0.002 ± 6.4E-05 | 0.02 ± 2.2E-03 | |

**b- Lettuce**

| Treatment | 2012 | | 2013 | | European Standard |
|---|---|---|---|---|---|
| | **[Cd]** ± SD mg.kg$^{-1}$ of FM | **[Pb]** ± SD mg.kg$^{-1}$ of FM | **[Cd]** ± SD mg.kg$^{-1}$ of FM | **[Pb]** ± SD mg.kg$^{-1}$ of FM | |
| C | 0.008 | 0.05 | 0.009 | 0.08 | |
| T1 | 0.006 | 0.04 | 0.009 | 0.04 | |
| T2 | 0.008 | 0.05 | 0.007 | 0.04 | **0.3** |
| T3 | 0.02 | 0.06 | 0.008 | 0.05 | |
| T4 | 0.007 | 0.06 | 0.006 | 0.08 | |

pods (Madre, Vergnes, Machon, & Clergeau, 2013).

Looking at a larger scale, many studies investigate ways to improve cities' resiliency and sustainability through food supply, energy, and nutrient cycles (MacRae et al., 2010; Grewal & Grewal, 2012; Billen, Barles, Garnier, Rouillard, & Benoit, 2008; Orsini et al., 2014). By using urban organic waste we insert our cropping system into the urban metabolism, ensure cheap access to substrate for gardeners, and reduce the city's waste treatment costs. For instance, coffee grounds with mycelium are a residue of an urban farm producing mushrooms from a previously unprocessed waste which is very common but still largely unknown today as a potential fertilizer. As an illustration, the annual production of coffee grounds by an average Parisian café is estimated at around 4 tons (Urban Farm personal communication). But this data has to consolidated. Other urban waste (organic and mineral) need to be tested, as it has been, to some extent, for other purposes (i.e. soil for urban trees, parks etc.) (Rokia et al., 2014Ostos et al., 2008). Possible optimal layout for production needs to be investigated. Apart from the advantages to use previously un-valorised urban waste, the ecosystem services potentially provided by this rooftop gardening (i.e provisioning services such as food production or food quality or regulation services such as flood regulation, climate regulation, carbon storage etc.) and their potential optimisation need to be studied.

Cropping sequences with too short a return time of a given crop in the same location are known to be unsustainable, especially from a sanitary point of view regarding parasitic species or plant diseases. In order to avoid these problems, since March 2014 our research team choose to work on pertinent diversified cropping sequences and crops associations. Furthermore, as Boudreau (2013) emphasizes, the majority of our knowledge on intercropping species is empirical and there is a need of scientific work on this question.

The remaining pollutants in edible production of urban agriculture are a key aspect of its development. In their study Saümel et al. demonstrated the possible effect of urban pollution (mainly from urban soil) on urban allotment gardens crops that are likely to be contaminated by trace metals (Säumel et al., 2012). As our results indicate, it is possible to produce edible crops in a dense city like Paris, with regards to levels of trace metals. In addition we have to point out the site-specific limits of our experiment: not close to a busy road, on one of the highest roofs in the area, and no known source of pollutants close by. Further investigations are however needed including the measurement of other pollutants (especially organic pollutants). As well as the understanding of the potential correlation between the roof's altitude or proximity to a highway and pollution levels.

## Conclusion

Green roofs have been studied extensively for their multiple benefits and generally consist of a thick layer of substrate with plants. There are currently 1.3 million m2 of green roofs in France mostly made up of exogenous substrate generally with a sedum plant covering. In this article we propose a new kind of green roof: a productive garden which is a form of Zero-Acreage farming designed to participate in the urban metabolism, primarily through the use of local urban organic waste. This could be an opportunity for cities, urban planners and even private building owners to solve the problem of the scarcity of land in dense cities like Paris. It may also be a solution to urban soil pollution risks facilitating the creation of new urban allotment garden and satisfying urban dwellers' demand for arable land. We have stressed the food producing potential of this new cropping system as well as the possibility of using rooftops even in cities like Paris.

Throughout the first two years of the experiment we witnessed a growing interest in our research by the media as by, inter alia, architects, restaurants, and public stakeholders. Thanks to the experiment a firm called Topager has emerged in the Parisian region and is now a partner in the experiment. Further investigations are needed to determine the real potential of Paris and of its suburbs for such productive rooftops. Using local organic waste and considering our cropping system as a living ecosystem that should be as functional as possible, shows interesting patterns that encourage us to pursue the research on different aspects, including the possible hurdles of such cropping systems (physical and/or chemical and/or biological); the influence and other possible biological inoculations; other


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urban substrates (mineral or organic) adapted to the local context; and the potential of rooftop gardening to be an habitat for urban plant and animal species. More generally, this underlines the necessity for research and quantification of the ecosystem services linked to this new type of green roof.

Climbing onto rooftops to create urban gardens is an opportunity to meet many needs of urban dwellers, and it offers new possibilities for urban planners.

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## Conflict of Interests

The authors hereby declare that there is no conflict of interests.

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## Annexes

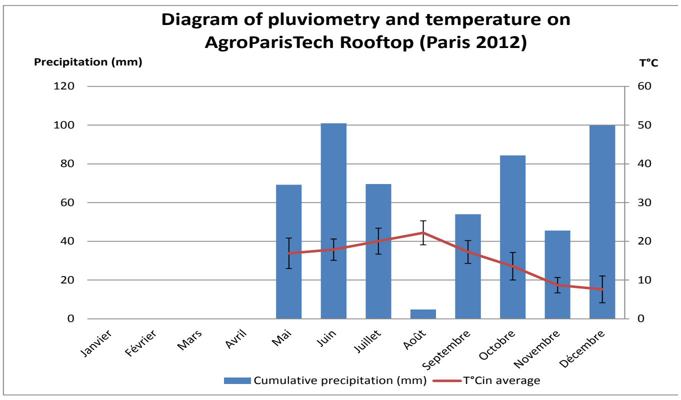
**Annex 1:** Description of the partner of the experiment T4P

BioYvelinesServices (*http://www.bioyvelines.fr/*) is a social-integration firm working for the valorization of green waste from the municipality of Versailles.
UpCycle (*http://www.laboiteachampignons.com/upcycle/* ) is a new and innovative urban farm that produces mushrooms (*Pleurotus Ostreatus* mainly) on coffee grounds for selling to gourmet restaurants. The firm operates in a social and solidarity economy involving disabled persons in the production cycle.

**Annex 2:** Potting soil composition

Potting soil "Terre à planter" Or brun brand.
Composition: Topsoil, blond sphagnum peat moss, composted bark, brown peat, horse manure and composted seaweed.

**Annex 3:** Meteorological condition for almost the entire two growing seasons



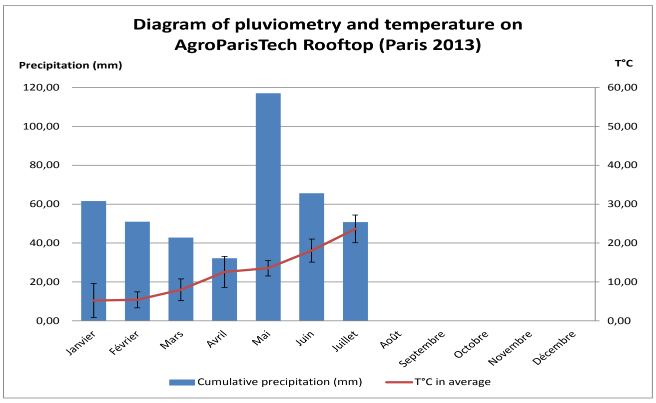




**Figure 5:** Rain and temperature for almost the entire two growing seasons.
Unfortunately, the data are not complete due to a problem with the meteorological stations on the roof.

## **Annex 4**: P-value from the ANOVA comparing the biomass production of each treatment

**Table 3:** p-values from the statistical analysis of the biomass production during the two growing seasons

| | T1 | T2 | T3 | T4 |
|---|---|---|---|---|
| C | 0,378883 | **0,0000971** | **0,0009214** | 0,8395126 |
| T1 | | **0,0009294** | **0,0134274** | 0,9011971 |
| T2 | p-value | | 0,3819518 | **0,0003128** |
| T3 | | p-value | p-value | **0,003718** |

Comparaison of yield per box of green manures per treatment in 2013

| | T1 | T2 | T3 | T4 |
|---|---|---|---|---|
| C | **0,003094** | **0,000723** | **0,001574** | 0,5897235 |
| T1 | | 0,8121444 | 0,9866147 | **0,0285028** |
| T2 | p-value | | 0,9732582 | **0,0055696** |
| T3 | | p-value | p-value | **0,0134479** |

Comparaison of yield per box of green manures per treatment in 2014

| | T1 | T2 | T3 | T4 |
|---|---|---|---|---|
| C | 0,634594 | 0,5002128 | **0,0081974** | 0,1247338 |
| T1 | | 0,9991145 | 0,0714591 | **0,0142077** |
| T2 | p-value | | 0,1033842 | **0,0098706** |
| T3 | | p-value | p-value | **0,0002285** |

Comparaison of yield per box of lettuce per treatment in 2012

| | T1 | T2 | T3 | T4 |
|---|---|---|---|---|
| C | 0,188174 | **0,0403131** | 0,2296012 | 0,3487934 |
| T1 | | 0,8431644 | 0,9998951 | **0,0094673** |
| T2 | p-value | | 0,7751587 | **0,0021949** |
| T3 | | p-value | p-value | **0,0116955** |

Comparaison of yield per box of lettuce per treatment in 2013

| | T1 | T2 | T3 | T4 |
|---|---|---|---|---|
| C | **0,020434** | **0,0035443** | **0,000001** | **0,0004499** |
| T1 | | 0,7626363 | **0,0000262** | 0,1176208 |
| T2 | p-value | | 0,000088 | 0,5539708 |
| T3 | | p-value | p-value | **0,0005368** |

Comparaison of yield per box of tomatoes per treatment in 2012

| | T1 | T2 | T3 | T4 |
|---|---|---|---|---|
| C | 0,999999 | 0,1055834 | **0,0317052** | 0,8488883 |
| T1 | | 0,1134095 | **0,0341171** | 0,8690501 |
| T2 | p-value | | 0,9310184 | 0,4220423 |
| T3 | | p-value | p-value | 0,147379 |

Comparaison of yield per box of tomatoes per treatment in 2013

## Annex 5: Fresh extrapolate weight for the first crop sequence during the two growing seasons

| | Green manure ± SD (kg/m²) | | Lettuce ± SD (kg/m²) | | Tomatoes ± SD (kg/m²) | |
|---|---|---|---|---|---|---|
| | 2013 | 2014 | 2012 | 2013 | 2012 | 2013 |
| C | 0,13 ± 0,04 | 0,30 ± 0,19 | 1,85 ± 0,39 | 1,38 ± 0,91 | 0,87 ± 0,08 | 3,80 ± 0,11 |
| T1 | 0,28 ± 0,1 | 1,48 ± 0,41 | 2,61 ± 0,33 | 2,29 ± 0,51 | 1,78 ± 0,09 | 3,86 ± 0,12 |
| T2 | 0,75 ± 0,17 | 1,72 ± 0,21 | 2,74 ± 0,25 | 2,67 ± 0,4 | 2,06 ± 0,12 | 4,80 ± 0,12 |
| T3 | 0,60 ± 0,07 | 1,59 ± 0,28 | 4,28 ± 0,33 | 2,23± 0,5 | 3,94 ± 0,33 | 5,07 ± 0,16 |
| T4 | 0,21 ± 0,04 | 0,41 ± 0,26 | 0,38 ± 0,32 | 0,63 ± 0,26 | 2,42 ± 0,18 | 4,19 ± 0,12 |

**Table 4:** Projected production for the cropping season 2012-2013 and 2013-2014. S-D: standard deviation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