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RESEARCH ARTICLE

Rooftop production of leafy vegetables can be profitable and less contaminated than farm-grown vegetables

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Abstract Urban agriculture may solve issues of feeding urban populations. In China, for example, densely packed mega cities will continue to expand in number and size, necessitating increasing food miles. Interestingly, it has been estimated that the total rooftop space in China is about 1 million hectares, some of which can be converted for rooftop farming. Yet, despite some favorable reports on urban farming, the Chinese commercial sector has shown little interest. This may be explained by the dearth of data comparing urban and conventional farming. Therefore, we present here a feasibility study of hydroponically grown vegetables in a rooftop screen house in Guangzhou, China. From December, 2012 to May, 2014, we tested the production of seven leafy vegetables that are easily perishable and are not well suited to long-distance transport. We calculated the production cost and measured biochemical parameters. Results show that levels of vitamin C, potassium, calcium, magnesium, iron, zinc, and crude fiber were comparable to market counterparts. None of the roof hydroponic vegetables exceeded the maximum residue limit for lead, arsenic, cadmium, chromium, mercury, or nitrate. In contrast, 5 of 98 market vegetables were contaminated by exceeding the maximum residue limit for lead. Similarly 3 were contaminated for arsenic, 23 for nitrate, and 2 for organophosphate or carbamate insecticide. Compared to high-end vegetables sold on the market, rooftop-grown vegetables were competitive in cost and quality. Given that many countries have limited arable land to feed a large population, the widespread adoption of rooftop hydroponics could help expand the total area available for food production as well as meet the rising demand for safe high-quality vegetables.

Keywords Urban agriculture · Rooftop farming · Z-farming · Leafy vegetables

1 Introduction

For many areas of the world, conventional farming is facing many challenges. Providing for the increasing needs of the world's rising population and its dietary change towards higher meat consumption has expanded and intensified agriculture to the point where it is becoming a serious threat to the environment (for review, see Foley et al. 2011). Cultivated land is decreasing with the rapid development of industrialization and urbanization, and farmland is losing fertility while increasingly being polluted, especially in the peri-urban zones that supply the readily perishable vegetables. Proposed as a means to augment conventional farming, arguments in favor of urban farming include benefits such as contributing to urban landscaping, decreasing the urban heat island effect, alleviating high transportation cost, reducing spoilage from long food distribution chains, providing food and jobs for city residents, and promoting food security and development (Mok et al. 2014; Eigenbrod & Gruda 2015; Goldstein et al. 2016). There are many types of urban farming, and roof farming is one type that does not directly compete for existing land use. Most roof space in urban areas is underutilized for auxiliary purposes beyond shelter. In most buildings, other than some space reserved for building maintenance and fire escape, much of the roof space is vacant. One estimate has placed

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the current available roof space in China at about 1 million hectares (Li 2012), equivalent to 0.8 % of the minimum 120 million hectares the Chinese government has reserved for cultivation. Total urban roof space will also increase due to the need to house another 200 million new urbanites in the next 30 years. Unlike indoor urban farming, roof farming uses predominantly natural sunlight that reduces the cost of artificial lighting.

In terms of yield, Astee and Kishnani (2010) estimated that rooftop farming could satisfy ~31 % of Singapore's vegetable needs. Grewal and Grewal (2012) used community garden soil production data to estimate that if 62 % of every industrial and commercial rooftop in Cleveland were used for agriculture, it could meet up to 32 % of the city's fresh produce needs. Orsini et al. (2014) extrapolated data from experimental plots that the available rooftops of Bologna, Italy, could satisfy 77 % of the city's vegetable requirement, and Sanyé-Mengual et al. (2015a) used literature data to estimate that 8 % of the rooftops of a typical logistics and industrial park in Barcelona, Spain, could provide tomatoes for about 150,000 residents. Aside from extrapolated estimates, Li et al. (2012) conducted large-scale planting on ~10,000 m^2 of flat and sloped roofs in Zhejiang Province, China, and reported that the yield of 23 vegetables, fruits, flowers, and grain crops was equal to or higher than conventional Chinese farming.

As for food safety, some studies have raised the concern of urban environmental pollution (Whittinghill & Rowe 2012; Specht et al. 2014). For instance, a recent study in Italy found that soil-grown vegetables in urban gardens have high heavy metal content, likely due to soil contamination near city roads (Antisari et al. 2015). However, Gelman (2014) tested vegetables on five different roofs in Helsinki, Finland, and found insignificant differences in PAHs and trace metals compared to market samples. Hu et al. (2015) surveyed vegetables collected from three rooftops in Hangzhou, China, and found that Pb, As, Cd, Cr, and Hg were all below the maximum residue limit. Grard et al. (2015) tested rooftop gardening in Paris using local urban organic waste as crop substrates and concluded high yield with low accumulation of heavy metals.

With respect to the environment, a recent review on urban green roofing describes positive effects on urban settings, including helping to clean the air of dust and smog and converting CO_2 to O_2 (Li and Babcock, 2014). As for rooftop vegetables, the experimental data from Taylor et al. (2012) of growing lettuce in a 19-m^2 net shack led to an estimate that if all of Manila's metropolitan area lettuces (1248 t annually) were supplied by roof hydroponics, ~2000 t of CO_2 would be reduced through reduced food miles and air conditioning (from lowering building temperature). Sanyé-Mengual et al. (2013) estimated that compared to conventional production methods for tomato production in Barcelona, Spain, a rooftop greenhouse system could save up to 74 % of the energy used for conventional farming. Orsini et al. (2014) projected that if all the flat rooftop surfaces in Bologna, Italy, were converted into rooftop gardens, it could result in the annual capture of about 624 t of CO_2.

Given that rooftop vegetable farming could benefit the environment and provide a significant proportion of vegetables for urbanites, it begs the question of why roof farming is not widely practiced. Local governments may take interest in improving urban landscaping, alleviating traffic congestion, providing jobs, and even reducing the carbon footprint, but widespread adoption of this new farming practice would likely require the active participation of the commercial sector. The one question that commercial enterprises ask are the experimental data (especially local data), rather than theoretical estimates, that roof farming can compete economically with conventional farming (or provide a higher return on investment than other uses like rooftop greening or solar panels). If the cost for roof farming is higher than those from other uses, then roof-derived vegetables will at best be relegated to individual or small community efforts.

In this study, we tested roof farming in Guangzhou (Canton), China, and compared rooftop cultivation against their market counterparts. The subtropical climate made it necessary to use a screen house to keep out as much as possible insect pests, although many studies on roof farming have used open-air systems, such as that described by Sanye-Mengual et al. (2015b) on testing nutrient film, floating hydroponics, and soil cultivation techniques on a building terrace in Bologna, Italy. We did not consider using soil because water draining out onto the roof is difficult to prevent, whereas properly managed hydroponic setups can contain the nutrient solutions without leakage. Soil is also a complex plant growth medium with biological ecosystems that may at times harbor non-beneficial organisms, and treating or replacing soil is more difficult compared with replacing hydroponic solutions and cleaning the solution tanks. A closed hydroponic system can reduce the use of water, the discharge of fertilizer, and plant uptake of pollutants.

Here, we report the testing of seven locally popular leafy greens that are not well suited for long distance transport, especially during the hot months of Guangzhou's subtropical climate. We find that roof farming can be competitive with conventional farming, but as with any study of this type, the data could be somewhat locale-specific. Nonetheless, this study serves as a guide for local decision makers to consider whether roof farming can take root on a broader scale than is currently operating.

2 Materials and methods

2.1 Screen house and hydroponics

A 25 × 6 m screen house (3 to 5 m in height) was erected to hold 14 hydroponic tanks on top of a two-story building that spans 28 × 9 m. This building within the South China Botanical Garden is about 450 m southeast of the 8-lane Tianyuan road and 400 m northwest of the 8-lane elevated South China Expressway (Fig. 1a, b). Traffic is typically heavy on both roads. The screen house comprises of a galvanized iron frame wrapped with insect screens, and an outer wrapping of plastic film on top and along the bottom half of the length of the screen house (Fig. 1c). A 30-cm high by 15-cm wide concrete border was built around the embedded iron columns. The screen house floor is tiled with skid resistant floor tiles. Hydroponic tanks are made from polyvinyl chloride typically used for tap water pipes. Each tank is 400 cm long, 100 cm wide, 10 cm deep, supported to a height of 80 cm off the ground by 4 sets of stainless steel legs, and holds 4 to 6 cm deep of nutrient solution recirculated by a small aquarium pump (35 w, 1100 L/h) for 5 min every 2 h (Fig. 1d). Static culture without recirculation of the nutrient solution is possible, but vegetables grow slower due to oxygen deprivation. Vegetables tested were caraway (*Coriandrum sativum* L.), Chinese flowering cabbage (*Brassica campestris* L.), crown daisy (*Chrysanthemum coronarium* L.), leaf lettuce (*Lactuca sativa var. longifoliaf. Lam*), leaf mustard (*Brassica juncea* L.), Italian lettuce (*Lactuca sativa* L.), and potherb mustard (*Brassica juncea var. multiceps*). Seeds were germinated in wet sponges, and after root lengths exceed 5 cm, sponge-wrapped seedlings were inserted into the holes of the hydroponic tank cover plates. Nutrient solution is formula B for leafy vegetables described by Liu (2001).

2.2 Chemical analysis

Two leafy vegetables consumed the most by local residents, Italian lettuce and Chinese flowering cabbage, were sampled twice a month between October 2010 and October 2011, alternating between vegetables from the Tianhe and the Haizhu districts of Guangzhou. For each kind, three quality grades were purchased from the market: (1) unlabeled common vegetables, (2) vegetables labeled as "pollution-free/green," and (3) vegetables labeled as organic. In China, pollution-free/green or organic vegetables are certified by the agriculture department upon meeting national standards and specific regulations. The organic label is reserved for vegetables grown without agro-chemicals such as inorganic fertilizer and pesticides while pollution-free/green vegetables are permitted limited use of agro-chemicals. Hydroponic Italian lettuce and Chinese flowering cabbage samples from our roof screen house were also collected, but for only 6 and 5 sample dates, respectively. In all, 31 samples of common Italian lettuce, 26 common Chinese flowering cabbage, 14 pollution-free/green Italian lettuce, 18 pollution-free/green Chinese flowering cabbage, 4 organic Italian lettuce, and 5 organic Chinese flowering cabbage samples were used. Vegetables sampled for experiments from different sources were of the same variety and approximately the same size, typically per plant

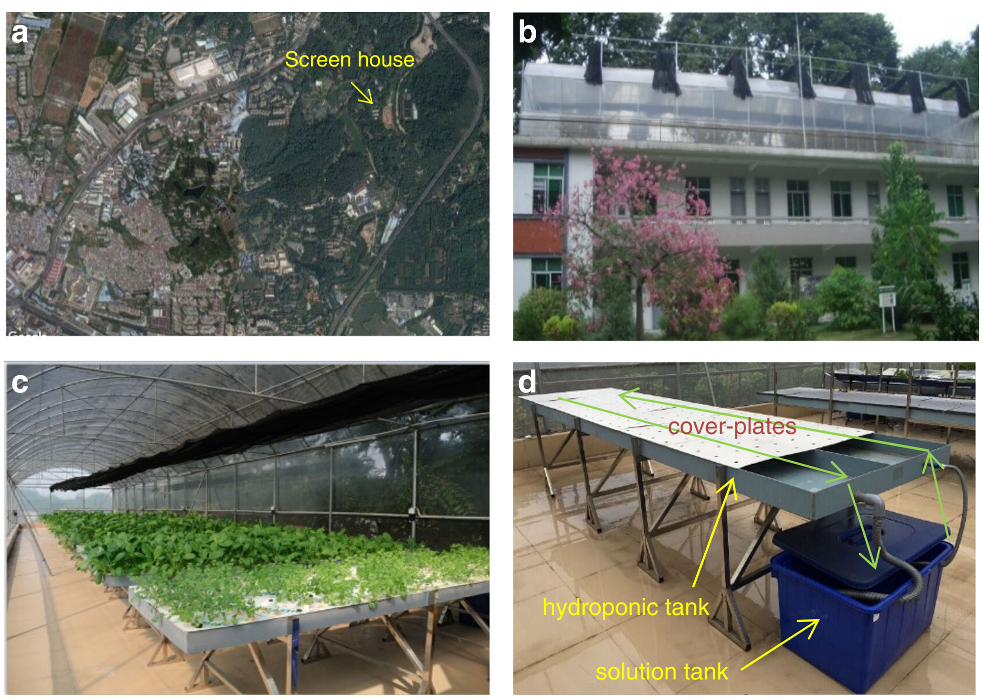

Fig. 1 Roof screen house and hydroponic setup. Location (**a**), exterior (**b**), and interior (**c**) of the rooftop screen house. **d** Hydroponic units showing the hydroponic and solution tanks and cover plates. Hydroponic tank divided by a partition; a water pump routes solution from to one side of the hydroponic tank to the other side via an opening at the far end of the hydroponic tank and then back to the solution tank (*green arrows*)

150 ± 30 g for Italian lettuce and 30 ± 5 g for Chinese flowering cabbage.

Given the generally suspected contamination of arable soils in this region, hydroponically grown leafy vegetables were compared against market counterparts with respect to the five most serious heavy metal contaminants, nitrate residues, and the most commonly used insecticides organophosphate and carbamate. Three vegetable samples of each of the four groups (common, pollution-free/green, organic, and hydroponic) were also randomly chosen for analysis of minerals, dietary fiber, and vitamins that are major nutrients of leafy greens. Since vitamin C changes quickly with post-harvest time and storage conditions, it is more difficult to ascertain with pollution-free/green or organic vegetables that are stored at the supermarket. However, common vegetables from street vendors should be fresh. Unsold vegetables are typically not marketable the next day due to a street vendor's lack of cold storage facility. Therefore, vitamin C content was compared only between three common and three hydroponic vegetables.

Vegetables were washed under tap water, patted dry with cotton towels; inedible parts were removed, and each sample was divided into three portions. Portion 1 was for determining pesticides and vitamin C content. Organophosphate and carbamate pesticide analyses were performed using a portable testing kit for an acetyl cholinesterase inhibition assay (China state standard GB/T5009.199–2003). Vitamin C content was determined following a 2,6-dichlorophenolindophenol titration method according to Harris & Olliver (1942). Portion 2 was frozen with liquid nitrogen and stored at −80 °C for subsequent nitrate analysis by the Griess-cadmium reduction and spectrophotometric method, using a flow injection analyzer (Quick Chem 8000, Lachat, USA) described by Prasad and Chetty (2008). Portion 3 was dried down for analysis of crude fiber, heavy metals, and minerals. Vegetables were dried in an atmospheric oven at 65 °C for ≥24 h until the weight became constant. Weight was recorded before and after drying to determine moisture content. The dried samples were homogenized to powder and stored in a vacuum desiccator. A measurement of 0.1 g of dry sample was digested with 6 mL 65 % HNO_3 (Merck Darmstadt, Germany) at 25 °C overnight, and further digested by a microwave sample preparation system (Multiwave 3000, Anton Paar, Austria). After digestion, the solutions were diluted with ultra-pure water to a final volume of 50 mL. Crude fiber was determined by a gravimetric method described by Mertens (2002), metals by inductively coupled plasma mass spectrometry (7700×, Agilent, Japan) according to Sanchez Lopez et al. (2003) and minerals (K, Ca, Mg, Fe, and Zn) by flame atomic absorption spectrometry (ContrAA 700, Analytikjena, Germany).

2.3 Cost analysis

The annual cost for facility/equipment is the straight-line depreciation expense with no salvage value (cost of asset/useful life of assets) for the screen house, the 14 sets of hydroponic setups, and miscellaneous greenhouse tools. Consumables include the costs of fertilizer, water, electricity, seeds, sponges, and packaging bags. Labor cost was based on actual (as well as typical) hourly wages for laborers in Guangzhou. Rent was hypothetically based on a cost that is tenfold higher than comparable rent for vegetable production in local suburbs. Yield/m^2/year data were converted from yield/tank data, equivalent to yield of 14 tanks/150 m^2 screen house/% of production days each year. Potential annual profit = (market price-cost of production)*deduced maximum yield/m^2/year.

3 Results and discussion

Given the higher load of insects in humid subtropical climates, it was necessary to grow vegetables within a structure that can keep out as much as possible insect pests, thereby minimizing pesticide applications. Construction of the 150-m^2 screen house in 2011 by an outside contractor took three construction workers 7 days to put up at a cost of ~¥86,000 RMB (Yuan unit of renminbi, Chinese currency) that included materials, construction, and a 15-year warranty, the length of time that the screen house is expected to last. This cost includes two changes of the plastic film as the films need replacing every 5 years. Temperature within was usually the same as ambient temperature except during sunny days when the temperature is generally 2 °C higher with the sunshade nets used. Without the sunshade nets, it was higher by as much as 8.5 °C in the winter and 15 °C in the summer. Light intensity was up to 38 % lower than outside the screen house, but still well above the level needed (20,000 lx) for most vegetables. Since construction, and up to the present time, the roof screen house has been strong enough to weather heavy rain including through four typhoon seasons. The total cost for the 14 hydroponic units, consisting of main tanks, stainless steel support legs, cover plates, solution tanks, water pumps, timers, and other miscellaneous items was ~¥35,000 RMB.

3.1 Feasibility of production

Leafy vegetables spoil easily after harvest and are not well suited to long distance transport. If grown within urban areas, the reduced distance to consumers may help preserve freshness as well as lower transportation costs to make them competitive against those grown outside urban centers. We tested 7 different locally grown leafy vegetables listed in Table 1. Yield per hydroponic tank was experimentally obtained for each vegetable in a typical production cycle, defined as the

Table 1 Yield and cost of roof hydroponic leafy vegetables

Vegetables	Days/production cycle	Optimal growing season	Suggested production cycles/year	Yield/tank (kg)	[a]Deduced maximum yield/m²/year (kg)	Cost(¥ RMB)							
						Facility, equipment/m²/year	[b]Consumables/m²/year	Labor/m²/year	Rent of roof/m²/year	Without rent		[c]With rent	
										Total/m²/year	Cost/kg	Total/m²/year	Cost/kg
Caraway	30	Oct–Feb	3	2.8	0.8	15.5	3.5	21.0	12.3	40.0	50.0	52	65.0
Chinese flowering cabbage	30	Oct–Apr	7	10.5	6.9	36.1	9.3	49.0	28.8	94.4	13.7	123	17.8
Crown daisy	45	Nov–Apr	3	7.9	2.2	23.2	4.2	21.0	18.5	48.4	22.0	67	30.5
Italian lettuce	45	Nov–Mar	3	23.3	6.5	23.2	4.0	16.8	18.5	44.0	6.8	63	9.7
Leaf lettuce	35	Oct–May	7	13.3	8.7	42.1	9.7	49.0	33.6	101	11.6	135	15.5
Leaf mustard	40	Jan–Dec	9	12.1	10.2	62.7	12.5	63.0	50.0	138	13.5	188	18.4
Potherb mustard	45	Oct–Jan	2	9.2	1.7	15.5	2.8	14.0	12.3	32.3	19.0	45	26.5
Italian lettuce	45	Nov–Mar	3	23.3	6.5		4.0	16.8		44.0			
Leaf mustard	40	Apr–Oct	5	12.1	5.6		7.0	35.0		76.7			
Year round (3 cycles lettuce +5 cycles mustard)					12.1	62.7	11.0	51.8	50	121	10.0	171	14.1

[a] Production cycles/year*yield/tank*14 tanks/150 m²

[b] Depending on the particular vegetable, the proportion of the consumables ranged from 6 to 11 % for fertilizer, 3–5 % for water, 3–6 % for electricity, 4–8 % for seeds, 35–71 % for sponges, and 8–29 % for packaging (bags)

[c] Rent was hypothetically based on ¥50 RMB/m² /year, tenfold higher than the typical ¥5 RMB/m² /year for vegetable production in local suburbs. ¥ *RMB* yuan, unit of renminbi (Chinese currency)

number of days to harvest from transplanting seedlings onto the hydroponic setup. The germination and seedling stage in nursery trays typically adds another 7 to 15 days to the length of time from seed to harvest, but are excluded from the production cycle as they do not require time in the hydroponic tanks. Other data in Table 1 are extrapolated based on using all 14 tanks of the 150 m² screen house. From our observations, only leaf mustard grew well throughout the year. Hence, the number of production cycles per year from this simple screen house setup is as low as 2 cycles for potherb mustard, but up to 9 cycles for leaf mustard.

Although configuring temperature control for cooling could extend the growing season for many of the vegetables, a more cost-effective solution would be to adjust the types of vegetables to grow. For example, by planting 3 cycles of Italian lettuce from November to March followed by 5 cycles of leaf mustard from April to October, the 150-m² screen house has the capacity for year-round production of 1800 kg (12.1 kg/m²) of leafy vegetables, or an average of ~5 kg per day. According to the China Nutrition Society's dietary guidelines, each adult should consume 0.3–0.5 kg vegetables per day (Liu, 2007). If we accept a simple assumption that leafy greens should account for about a third by weight of the total vegetables consumed, 5 kg per day could provide the green leafy vegetable needs for 30–50 individuals.

If the same roof area (252 m²) were on top of a residential building, each floor below would likely comprise of two apartments of ~110 m². Assuming each floor houses 8 persons, or 2 families of 4, that would mean the 150-m² screen house has the capacity to provide the green leafy vegetable needs for 4 to 6 floors of inhabitants. Realistically, however, it is unlikely that people would want to be confined to only leaf mustard and Italian lettuce, as suggested for maximum production, or even to the limited list of green leafy vegetables shown in Table 1. Most likely, they would rather supplement their diet with other leafy greens from the market. Given that assumption, roof farming would provide only a portion of green leafy vegetable needs. Nevertheless, even if a 150-m² screen house provides just a quarter of the green leafy vegetables for 16 to 24 floors of inhabitants, it is still a significant contribution from roof space.

3.2 Safety of production

With Italian lettuce, all samples showed nitrate content below the maximum residue limit (Fig. 2). However, 23 of 49 Chinese flowering cabbage samples from the market had nitrate content exceeding the maximum residue limit, even those labeled as pollution-free/green or organic. In contrast, none of the hydroponic vegetables exceeded the maximum residue limit for nitrate. The presence of pesticides has been a concern since the Agriculture Bureau of Guangzhou-Vegetable Office reported that 10.7 % of the vegetables contained excessive pesticide residues when 54 kinds of pesticides were determined by high-pressure liquid chromatography (Guangzhou Agriculture Website 2012). When the less sensitive acetyl cholinesterase inhibition method was used, the rate of detection was only 0.9 %. We had previously conducted a farmer's survey of the various pesticides used in the Guangzhou area and noted that organophosphate and carbamate insecticides were in common use (Yang et al. 2014). With the acetyl cholinesterase inhibition assay, we found that among 98 market samples, only one common Chinese flowering cabbage sample showed clear contamination, while surprisingly, one pollution-free/green Chinese flowering cabbage showed slight contamination (data not shown). In contrast, these pesticide residues were not found in our hydroponically grown vegetables. During our 2 years of growing vegetables, pest infestation occurred in three instances: aphids in the autumn of 2012, diamondback moths in the spring of 2013, and gray mold in lettuce during the rainy days of spring 2013. However, in each instance, they were effectively controlled by spraying low doses of low toxicity avermectin pesticide immediately after the occurrence, or by removing infected plants and cleaning the affected facility. Overall, there was not much of a need for using pesticides.

With respect to heavy metals, routine quality and safety monitoring by the Guangzhou Agricultural Product Quality Safety Supervision and Inspection Center showed that in 2011, 5.3 % of the market vegetables contained lead, cadmium, chromium, or mercury above the maximum residue limit

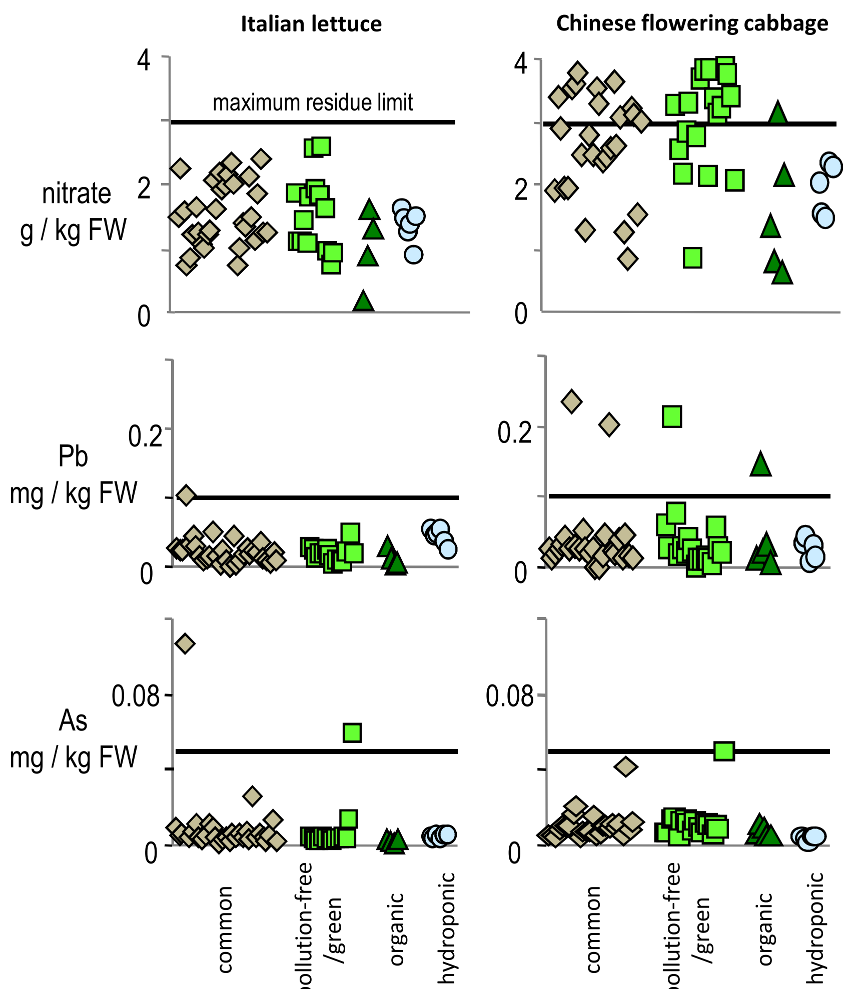

Fig. 2 Comparable or lower nitrate and heavy metal (Pb, As) content of roof hydroponic vegetables over market counterparts. *Horizontal bar* indicates maximum residue limit from China state standards, safety requirements for non-environmental pollution vegetable (GB18406.1-2001; GB2762-2005)

(Guangzhou Agriculture Website 2012). In our analysis of 109 samples, excessive amounts of Cd, Cr, or Hg were not found (data not shown). However, one Italian lettuce sample and four Chinese flowering cabbage samples exceeded the maximum residue limit for Pb (Fig. 2), and two Italian lettuce samples exceeded the maximum residue limit for As (Fig. 2). The contamination was not confined to common vegetables, but included pollution-free/green and organic samples. In contrast, all five heavy metals were low in the hydroponic vegetables. This is likely due to the ability to control the content of the hydroponic solution, which aside from plant nutrients was otherwise municipal grade tap water. This agrees with the report by Antisari et al. (2015) that soil-less planting systems can reduce the accumulation of heavy metals, such as up to 71 % in rosemary leaves.

3.3 Quality of production

As for minerals, hydroponic Italian lettuce contains the highest Ca, K, Mg, and Fe but the lowest Zn content, while hydroponic Chinese flowering cabbage contains the highest Ca and K but lowest Fe and Zn (Fig. 3). Common and organic vegetables were found to have higher crude fiber than pollution-free/green and hydroponic vegetables (Fig. 3), and this may be due to their outdoor growth, as opposed to the hydroponic and pollution-free/green vegetables that thrive in relatively protected environments. Less fiber can be desirable as the vegetables have a more tender texture. As shown in Fig. 3, the vitamin C content of the hydroponic vegetables was higher than their market counterparts.

This agrees with other studies that also concluded high-quality vegetables from soil-less cultivation (Gruda 2009).

3.4 Cost of production

The cost in year 2011 for erecting the roof screen house and its interior was ~¥120,000 RMB. Spreading the cost over the life expectancy of the facility and equipment, the cost for the facility is ¥62.7 RMB/m^2/year. Because differences exist among vegetables with respect to planting density, nutrient solution, workload, production cycle, and unit yield, the costs were calculated individually for each type of vegetable (Table 1). Cost of facility and equipment range from ¥15.5 to ¥62.7, consumables ¥2.8 to ¥12.5, and labor ¥14 to ¥63 RMB/m^2/year. The cost of consumables (less than 10 % of the total) includes utilities which were rather inexpensive. Water was used for the solution and the occasional cleaning of the tanks and floors, and electricity was mainly for small water pumps that operate only 5 min every 2 h. This works out to a total (facility, consumables, labor) cost/kg of ¥6.8 RMB for Italian lettuce to ¥50 RMB for caraway. Due to the clean production method, we expect that the hydroponic vegetables can be comparable in

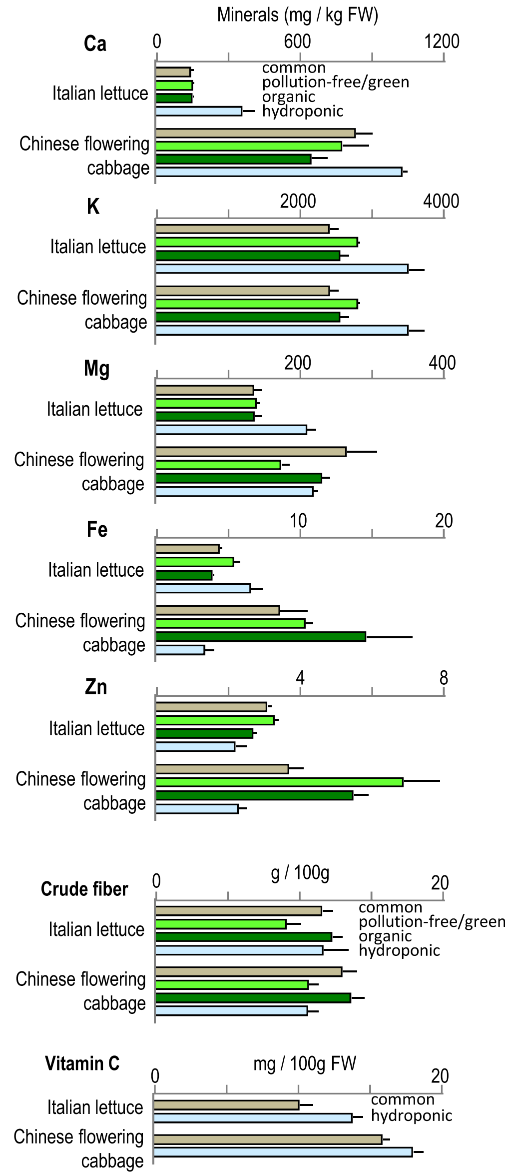

Fig. 3 Comparable nutrient content of roof hydroponic vegetables. Vitamin C, the minerals K, Ca, Mg, Fe, Zn, and crude fiber were all within a range comparable to market counterparts. Value is the mean ± standard error of three samples (each sample measured three times)

quality to pollution-free/green vegetables. Therefore, the typical market prices of pollution-free/green vegetables were used for reference (Fig. 4). For all vegetables except for caraway, the cost of production is less (27 to 52 %) than market price (Fig. 4), with highest potential profit for leaf mustard at ¥296 RMB/m^2/year (¥44,400 RMB/150 m^2 screen house). This is even higher than the potential profit for maximum kilogram yield from 3 cycles of Italian lettuce and 5 cycles of leaf mustard (¥282 RMB/m^2/year) due to the lower market value of Italian lettuce, although these figures do not include the costs for rent, distribution, packaging, and advertising.

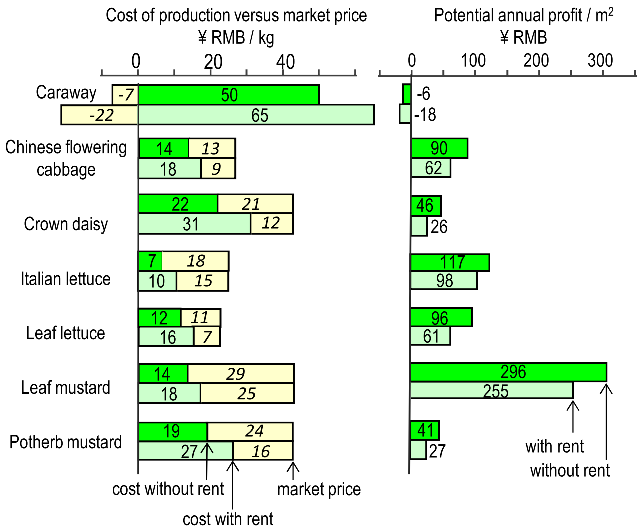

Fig. 4 Economic feasibility of rooftop hydroponics. *Left panel*: cost/kg of roof hydroponic vegetables with or without hypothetical rent (Table 1) versus market price pollution-free/green vegetables (rounded to nearest whole ¥ RMB). *Numbers in italic* show difference between cost and market price. *Right panel*: potential profit = (market price-cost of production with or without hypothetical rent)*deduced maximum yield/m^2/year (Table 1). Pollution-free/green lettuce, Chinese flowering cabbage, and leaf lettuce from Guangzhou Dongsheng organic farm, Guangzhou, China; other vegetables from Guangzhou Jinhe Agriculture Co. Ltd. (2011.10–2015.05). *¥ RMB* yuan unit of renminbi (Chinese currency)

Substantial distribution cost can be averted if vegetables from the roof are sold to building residents. In such a scenario, vegetables would only need an elevator ride for distribution to individual households within a residential building. As for packaging, instead of the polystyrene foam trays and plastic wrappings of premium vegetables in supermarkets, freshly harvested ones can be delivered with reusable bags or baskets. Such a distribution system not only reduces labor cost, but also ensures freshness. Rent, however, is difficult to estimate for the cost of space that customarily is not used. As a reference, land for vegetable production in local suburbs is ¥5 RMB/m^2/year according to our survey. Even if it is tenfold higher, at ¥50 RMB/m^2/year, it would only amount to ¥12,600 RMB per year for the entire 252-m^2 roof, reducing the estimated leaf mustard profit from ¥44,400 (¥296/m^2) to ¥31,800 RMB.

We specifically chose to test only leafy vegetables because they are readily perishable and would benefit the most from local production. They also have a relatively shorter production cycle that reduces cost. Most of the biomass is consumable, whereas growing crops with a high amount of plant waste, such as rice stalks that must be transported from the roof for disposal, would increase the cost of production. Our study also benefitted from the geographical advantage of the warm South China climate that precludes the need for a glass or polycarbonate encased greenhouse. A relatively inexpensive screen house is sufficient to keep insects out and protect crops from heavy rain. Eliminating glass or polycarbonate not only reduces construction costs, but enhances safety by reducing the possible shattering and falling of dangerous materials from the roof. Hence, we do not view our experience in roof farming in a warm climate as universally applicable. However, even if it is confined to Guangzhou with its 13 million residents, the Guangdong Province with 104 million residents, or to South China with an even a larger population, it is a sizable geographical area with ample potential for this type of roof farming practice.

As for alternate uses of roof space, rooftop greening has received popular attention with many local governments as a way to combat urban air pollution (for review, see Li and Babcock, 2014), but if it is merely gardening, it most likely does not generate direct profits. As for solar energy, current technology should be able to generate ~546 Wh/day/m^2 using the most efficient solar panels (Li et al. 2013). In the case of our 252-m^2 rooftop, it could potentially generate some ~138 kWh/day of electricity with some losses in conversion efficiency, although the smog in most Chinese cities would likely reduce this production potential. That might be sufficient to power eight households without air conditioning. However, solar generated electricity is still rather expensive and currently requires government subsidies.

4 Conclusions

Studies have previously suggested that rooftop farming can be a valuable supplement to conventional farming, particularly with locally popular vegetables (e.g., Astee and Kishnani 2010; Li et al. 2012; Taylor et al. 2012; Whittinghill & Rowe 2012; Specht et al. 2014; Orsini et al. 2014; Eigenbrod & Gruda 2015; Sanyé-Mengual et al. 2015a; Goldstein et al. 2016). We further confirm that certain leafy vegetables can be as productive in yield and quality as those sold by local farms. More importantly, we present experimental data that at least for certain vegetables grown in the subtropical South China climate, this type of farming can be profitable. However, whether this may provide sufficient incentive to further advance the commercialization of roof farming for food production could also depend on alternative uses for rooftop space, although the different options are not mutually exclusive. For the construction of new urban districts, the possibility could exist that different buildings or sections of a roof could serve different purposes, including recreation, roof greening, solar energy, and roof farming. However the roof is used, it is still more productive than leaving it vacant, as is commonly the case in today's urban settings.

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