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Urban agriculture: a global analysis of the space constraint to meet urban vegetable demand

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Abstract

Urban agriculture (UA) has been drawing a lot of attention recently for several reasons: the majority of the world population has shifted from living in rural to urban areas; the environmental impact of agriculture is a matter of rising concern; and food insecurity, especially the accessibility of food, remains a major challenge. UA has often been proposed as a solution to some of these issues, for example by producing food in places where population density is highest, reducing transportation costs, connecting people directly to food systems and using urban areas efficiently. However, to date no study has examined how much food could actually be produced in urban areas at the global scale. Here we use a simple approach, based on different global-scale datasets, to assess to what extent UA is constrained by the existing amount of urban space. Our results suggest that UA would require roughly one third of the total global urban area to meet the global vegetable consumption of urban dwellers. This estimate does not consider how much urban area may actually be suitable and available for UA, which likely varies substantially around the world and according to the type of UA performed. Further, this global average value masks variations of more than two orders of magnitude among individual countries. The variations in the space required across countries derive mostly from variations in urban population density, and much less from variations in yields or per capita consumption. Overall, the space required is regrettably the highest where UA is most needed, i.e., in more food insecure countries. We also show that smaller urban clusters (i.e., <100 km^2 each) together represent about two thirds of the global urban extent; thus UA discourse and policies should not focus on large cities exclusively, but should also target smaller urban areas that offer the greatest potential in terms of physical space.

S Online supplementary data available from stacks.iop.org/ERL/9/064025/mmedia

Keywords: urban agriculture, urban land use, food security, global vegetable demand, area required

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1. Introduction

The majority of people today live in urban environments, and it is estimated that future population growth will be concentrated in urban areas of less developed countries, while global rural population is expected to decline after 2020

(UN 2010). Thus it has been proposed by many that by growing food in or near urban areas, one can more effectively deliver food to people and reduce the environmental costs of agriculture (Despommier 2011), especially the costs involved in transporting food (Deelstra and Girardet 2000, Perkins 1999, UNDP 1996). These and other arguments have recently revitalized the interest in urban agriculture (UA) and contribute to the ongoing debate about its advantages and drawbacks (Bryld 2003, McArdle 2013, The Economist 2010, The Times 2004). Conceptualizing what 'urban' precisely means remains a challenge (Montgomery 2008), but broadly speaking urban areas consist of predominantly human-made surfaces, have high concentrations of people, and are the hub of economic activity. For our analyses, we used a definition of 'urban' that is ultimately based on the presence of human-made surfaces (see materials and methods).

From subsistence backyard gardening in Harare (Dongus *et al* 2009) through systematic social participatory involvement in Cuba (Novo and Murphy 2000) to for-profit rooftop greenhouses in North America (e.g., Lufa Farms in Montréal; http://lufa.com/en/), UA involves a wide range of people and practices (Mougeot 2000). UA is generally defined as the practice of growing crops and grazing livestock in urban, suburban and peri-urban areas (UNDP 1996), and is often proposed as an environmentally friendly agricultural production method, providing food in the place of highest demand with available labor (Satterthwaite *et al* 2010, Smit and Nasr 1992). Conversely, UA has been criticized for its potentially high-energy demand and concerns about health and safety related to contamination and diseases (Cofie *et al* 2005, Dongus *et al* 2009, Ellis and Sumberg 1998).

The current scale of UA is difficult to assess. The limited evidence, which is often qualitative and sometimes anecdotal, suggests that UA is currently an important reality for many households, particularly in developing countries (FAO 2010, Zezza and Tasciotti 2010). A widely cited 1996 survey estimated that about 800 million people (i.e., ~15% of the world population at that time) were involved in UA (UNDP 1996). However, this estimate was based on expert judgement. Studies have quantified the potential contribution of UA to food production and consumption for a few cities, generally in developed countries (Duchemin *et al* 2009, Grewal and Grewal 2012, MacRae *et al* 2010, Urban Design Lab 2012), but no such assessment has been performed at the global scale. Also, since much of the current focus is on large cities, little is known about UA in smaller urban areas (Thornton 2008).

Given that UA must, by definition, happen within the boundaries of urban areas, the limited extent of urban space is a basic and universal feature that can constrain the capacity of UA to provide food to urban dwellers. Therefore, the purpose of this study is to provide the first global-scale assessment of the urban space constraint for satisfying the food needs of urban dwellers through UA. More precisely, we addressed the following two questions for the vast majority of countries around the world.

Table 1. Global urban area and global annual harvested area for vegetables and cereals (in mega-hectares) for the 165 countries included in our study.

Element (circa 2001)	Area (Mha)
Global urban area	64.3
Global annual harvested area for vegetables	47.2
Global annual harvested area for cereals	661.6

i. *What percentage of the existing urban area needs to be devoted to UA to meet the vegetable consumption of urban dwellers in different countries of the world?* Although a significant number of people, especially in developing countries, produce staple crops through UA (Maxwell 1995, Safi *et al* 2011, Zezza and Tasciotti 2010), we restricted our study to vegetables for several reasons. First, comparing global annual harvested areas for vegetables and cereals to global urban area highlights the limited potential contribution of UA to global cereals production (table 1). Second, studies suggest that, compared to staple crops, the production of high-yielding, high-value and perishable products like vegetables often represent the most profitable UA endeavor and constitute a substantial fraction of UA production in practice (Lee-Smith 2010, Safi *et al* 2011, Vagneron 2007). Finally, a key contribution of UA is in increasing the dietary diversity through the incorporation of vegetables into the diet to address food insecurity (Frison *et al* 2006, Welch and Graham 1999, Zezza and Tasciotti 2010).

ii. *How is the total urban area distributed among urban clusters of different sizes, at the global scale and for each country individually?* This analysis will reveal whether UA potential resides mostly in smaller or larger urban areas. As the majority of urban dwellers live in small and medium (in terms of population) urban areas (Cohen 2006, Montgomery 2008, UN 2004), the current focus of UA on large cities seems *a priori* unwarranted.

The objective of our study is to quantify the percentage of each nation's total urban area that would be needed to match two different vegetable production targets, thereby quantifying how limiting is urban space itself for UA to feed urban dwellers around the world. Note that we are not investigating whether this required urban area is actually available in each country. Indeed, numerous local-scale factors like regulations and competing demand for land also constrain UA in practice (see Mougeot (2006) for various examples of cases studies from different continents) but are beyond the scope of this research. However, if our estimate of required urban area for UA is greater than 100% of the country's total urban area, then space is a clear limitation, even without considering these other local-scale factors. Note that our results are not formal projections for the coming decades, but are rather based on reported data for the recent time period and are therefore representative of the current situation.

2. Materials and methods

Quantifying how much food UA could potentially produce around the world would require a global-scale dataset on the actual areas available for UA. Not only does such a dataset currently not exist, but the areas deemed 'available' would also need to vary according to the type of UA considered (e.g., backyard or rooftop UA). Consequently, we developed an approach that circumvents these limitations by estimating, for each country, the proportion of the total urban area needed to meet certain consumption targets (see below). As a consequence, no assumption was needed about the actual availability of urban area for UA. Since computations were performed at the national level, the results account for differences in UA production and consumption among, but not within, countries (see the online supplementary material available at stacks.iop.org/ERL/9/064025/mmedia for more details on the materials and methods).

2.1. Global datasets

The definition of urban area varies greatly across the world. Although it generally features high population density and large (almost) continuous human-made surfaces, there are large variations in thresholds used for population density, landuse, etc Therefore, in order to quantify with a globally consistent methodology the total urban area in each country, we favoured a land-cover based approach. We used the global urban dataset derived from the 500 m MODerate resolution Imaging Spectroradiometer (MODIS) circa year 2001 (Schneider *et al* 2009, 2010). The MODIS dataset was evaluated to be superior to other available global datasets of urban area (Potere *et al* 2009). In this dataset, the ~500 m pixels are classified as urban when more than 50% of their area is covered by built-up land and when they belong to contiguous patches of built-up land greater than 1 km^2. The dataset thus aims to exclude large urban parks (e.g., Central Park in New York), but does include some non-impervious surfaces (e.g., standard backyards). The total urban area within each country was then summarized using the Global ADMinistrative (GADM) dataset v2.0 (GADM 2012).

From the FAOSTAT database (FAO 2012), we extracted country-specific data on:

i. agricultural production and harvested area for the 'vegetables and melons' group (27 crops, henceforth 'vegetables'; data are available for each crop);
ii. vegetable 'food supply quantity', used as a proxy for household-level consumption[4] (not available for each crop, but only for vegetables as a group); and
iii. population (total and urban).

Each variable was then averaged over a five-year time window centered on 2001. Since very few empirical studies focusing on UA measured crop yields in urban areas, we assumed that, for each crop in each country, the UA yield equals the average national yield for conventional farming as reported by FAOSTAT (see the discussion). Additional quality-control procedures led to a final list of 165 countries included in our study (see supplementary material SM 1.1 for more details on the global datasets).

2.2. Analysis 1: Percentage of urban Area Needed (PAN)

The main impetus of this study is to quantify the Percentage of urban Area Needed (PAN, in %) to produce sufficient vegetables through UA to meet two different targets of actual and recommended vegetable consumption.

Target A: Meet *actual* vegetable consumption by urban dwellers circa 2001 (i.e., we scaled national consumption by the urban-to-total population ratio, assuming similar urban and rural per capita consumption).
Target R: Provide 300 g of vegetables per capita per day to urban dwellers. This value came from the joint FAO/WHO *recommendation* of a minimum daily intake of 400 g of 'fruit and vegetables' to prevent chronic diseases and micronutrient deficiencies (FAO/WHO 2004), and from the global mean vegetable consumption of 319 g/cap/day for urban dwellers that we computed from the FAOSTAT dataset. We set this second target because, in many countries, actual vegetable consumption is below recommended levels (He *et al* 2007). Indeed, the FAOSTAT data used here indicate that vegetable consumption is below 300 g/cap/day in 126 of the 165 countries studied.

In a given country *i*, the *PAN* required to satisfy each target ('*goal*' in equation (1)) is calculated according to:

$$PAN(i) = 100 \times \sum_{k=1}^{N} \frac{\text{goal}_{\text{prod}}(i, k)}{\max_{\text{prod}}(i, k)} \tag{1}$$

where the sum is performed over the 27 different crops ($N = 27$). The numerator gives the target production (in tonnes) for crop *k*, while the denominator gives the maximum production (in tonnes) if all the urban area were allocated to growing this crop (supplementary material SM 1.2 and 1.3). Note that the *PAN* values are directly proportional to their corresponding target. For example, if *PAN* is 40% for target A in a given country, then this country could produce half its actual urban vegetable consumption on 20% of its urban area.

Since the FAOSTAT dataset does not provide country-level consumption for each vegetable crop (but only for vegetables as a group), we assumed that the UA mix of vegetable crops consumed in each country was the same, in relative terms, as the mix of vegetable crops produced in the larger region to which the country belongs (supplementary material SM 1.3). This intermediate approach is preferable over using the country-level production mix (which would neglect the role of trade) or the continent or global production mix (which would over-homogenize consumption across countries).

[4] Note that 'food supply quantity' provides a measure of food availability at the household level, and is different from 'domestic supply quantity' which only accounts for production, imports, exports, and stock changes.

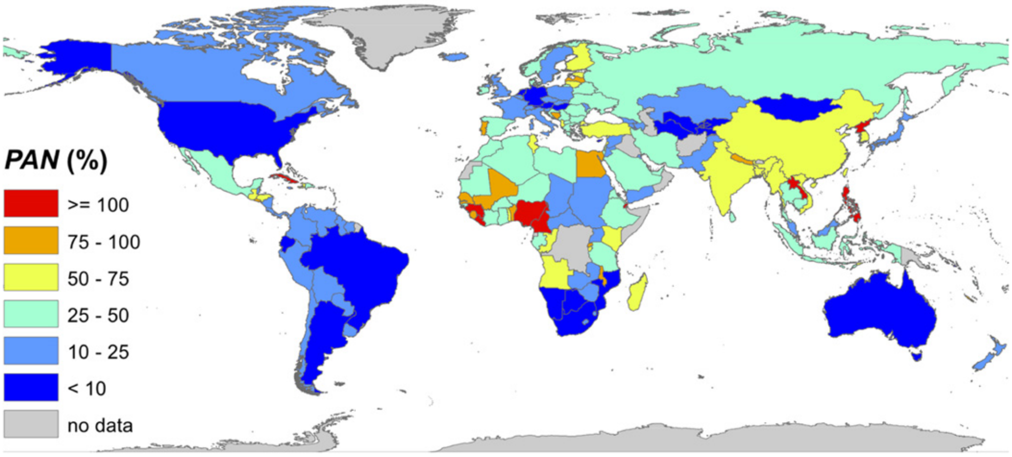

Figure 1. PAN_a (*Percentage of urban Area Needed*) to meet the actual consumption of vegetables by urban dwellers through UA (target A).

Table 2. Frequency distribution of countries by PAN^a classes for $PAN_a{}^b$ and $PAN_r{}^c$, with the corresponding share of the global urban population (in %).

	<10%	⩾10% & <25%	⩾25% & <50%	⩾50% & <75%	⩾75% & <100%	⩾100%	Total
PAN_a	22	52	39	27	14	11	165
Share of global urban population (%)	19.9	18.8	20	34.7	2.1	4.5	100
PAN_r	9	38	39	17	11	51	165
Share of global urban population (%)	11.4	16.7	38.6	6.9	16.8	9.6	100

[a] *PAN* = *Percentage of urban Area Needed* to meet the target.
[b] PAN_a = meet the actual consumption of vegetables by urban dwellers.
[c] PAN_r = meet the recommended consumption of vegetables by urban dwellers.

2.3. Analysis 2: size distribution of urban clusters

We used the MODIS dataset to quantify the share of the total urban area occupied by urban clusters of different sizes, globally as well as for each country. To this end, we used spatial contiguity rules to group urban pixels and we then assigned each resulting urban cluster to one of the following four extent classes, based on a logarithmic scale (supplementary material SM 1.4): (1) less than 10 km^2, small; (2) 10–100 km^2, medium; (3) 100–1000 km^2, large; and (4) 1000 km^2 and above, very large. There is no perfect one-to-one correspondence between individual 'urban clusters', which are defined as contiguous built-up areas, and individual 'cities', which are administrative units. Nevertheless, urban clusters are generally good proxies for cities. For example, New York, Paris, and Shanghai were classified as 'very large' clusters, whereas Montréal, Frankfurt, and Santiago de Chile were classified as 'large' clusters.

3. Results

The *PAN* results for target A (henceforth 'PAN_a') show that, according to the datasets we used, 11 countries do not have enough urban area to satisfy the actual vegetable consumption of their urban population, whereas 22 countries need to set aside less than 10% of their urban area to do so (figure 1 and table 2). Countries that need to devote a quarter or less of their urban area to UA to satisfy target A host 39% of the global urban population (table 2), with 12 of these 74 countries being in Africa and two being in South or South-Eastern Asia. The global mean PAN_a value across the 165 countries (supplementary material SM 1.2) is 30%, i.e., less than a third of the global urban area needs to be devoted to UA in order to produce all the vegetables consumed by urban dwellers. However, this mean value of 30% masks differences of more than two orders of magnitude (from 1.2% to 397.4%) among individual countries.

Assuming instead that UA would need to produce 300 g/cap/day of vegetables in all countries (i.e., the recommended diet) changes the results substantially (figure 2 and table 2). Indeed, only nine countries have a *PAN* lower than 10% for target R (henceforth 'PAN_r') and 51 countries would have insufficient urban area to meet the recommended diet. Also, the countries with a PAN_r of 25% or less host a smaller population (28% of the global urban population) compared to target A (table 2). Only two of these 47 countries with $PAN_r \leqslant 25\%$ are in Africa and none is in South or South-Eastern Asia, while 23 are OECD member countries (OECD 2012). The global mean PAN_r value of 35% (this time, results vary from 4.2% to 1021.0% among individual countries) is slightly higher than the global mean PAN_a value

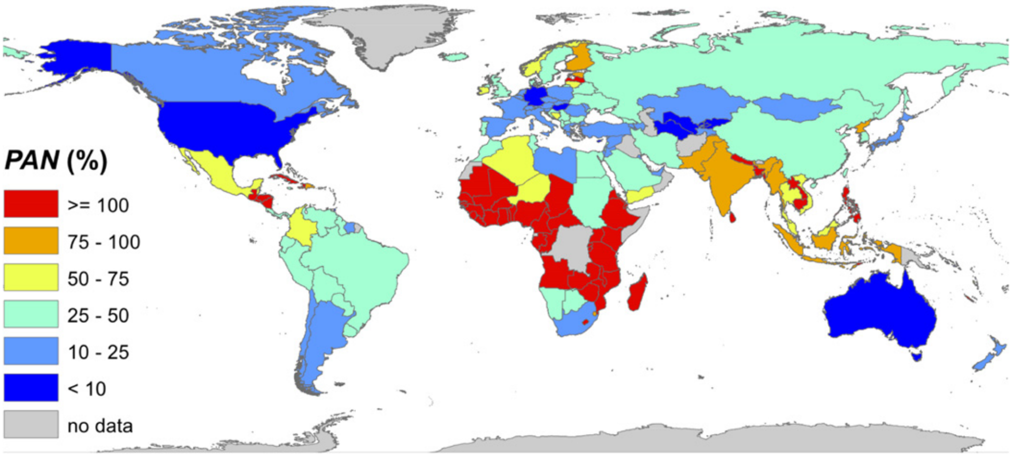

Figure 2. PAN_r (*percentage of urban area needed*) to meet the recommended consumption of vegetables by urban dwellers through UA (target R).

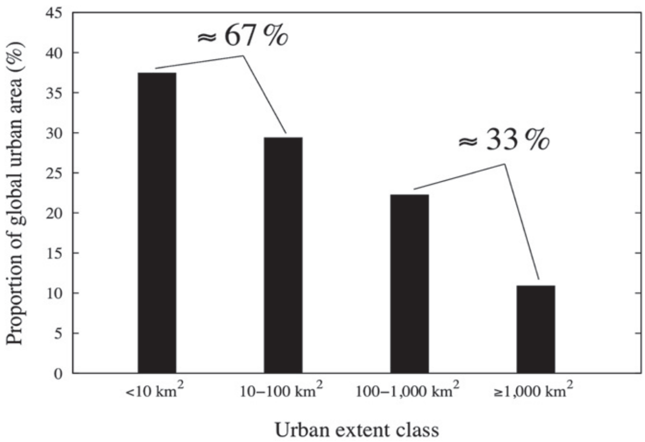

Figure 3. Distribution of the global urban area by classes of urban extent.

of 30%. Since the global production of vegetables is actually lower for target R than for target A (300 versus 319 g/cap/day), this outcome stems from the changes in the distribution of UA production among individual countries, and illustrates the fact that actual vegetables consumption is lower than recommended in most countries of the world.

The clustering analysis indicates that about two thirds of the total urban area at the global scale is constituted by small and medium clusters (figure 3). In 155 of the 165 countries we analyzed, more than 50% of the total national urban area is occupied by small and medium urban clusters. If we assume that UA yields are similar for all urban cluster sizes within a country, smaller-sized urban areas can therefore contribute substantially more to UA production than larger ones. Moreover, it is likely that the smaller urban areas, with lower population densities, can actually devote a higher proportion of their area to UA.

4. Discussion

This study represents the first global-scale assessment of the proportion of urban area needed to meet urban food demand. UA is generally practiced on communal gardens, in private backyards, or on idle land, balconies or rooftops (Duchemin *et al* 2009), in other words in areas that are not fully exploited and that can serve multiple uses. Due to the lack of detailed data on the proportion of urban space that could actually be used for UA, it is impossible to accurately compute how much food can be produced under UA at the global scale. Thus, this study focused on the *PAN* in each country to meet the vegetable consumption of urban dwellers, for two different targets (i.e., the amount that is actually consumed in the country or a recommended 300 g/cap/day).

The main outcomes of this study are threefold. First, the results highlight the high variability of *PAN* values across countries. Indeed, for both targets, the largest national *PAN* estimate is more than 240 times greater than the smallest one. A further assessment of the influence of the key factors varying among countries (urban population density and yields for both targets, as well as per capita vegetable consumption for target A) clearly shows that urban population density has the highest impact on *PAN* (supplementary material SM 2.1). For example, PAN_a for El Salvador is almost three times higher than the value for Bulgaria despite higher effective yields (49% higher, accounting for the UA mix of crops) and lower per capita vegetable consumption (almost three times lower), because urban population density is about ten times higher in El Salvador than in Bulgaria. This suggests that the amount of space available per capita is a major limiting factor for UA, which is in agreement with empirical studies highlighting the importance of land availability and access (Lynch *et al* 2001, MacRae *et al* 2010, Maxwell 1995, Vagneron 2007). It has also often been observed that UA can be displaced with increasing growth and development of cities due to increasing competition for land (Lee-Smith 2010, Vagneron 2007). This indicates that the potential contribution of UA to food consumption is likely much higher for less

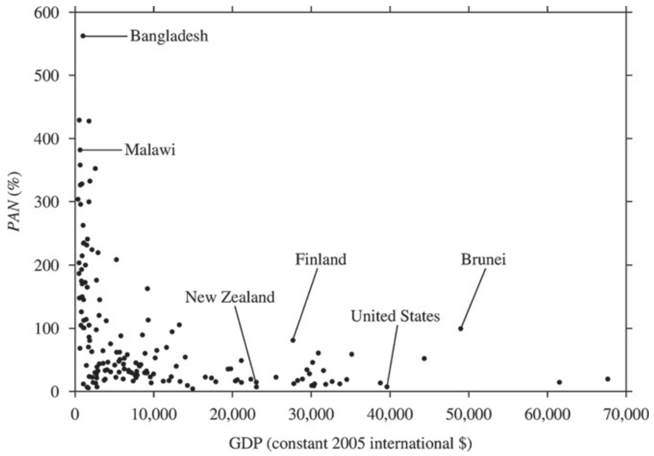

Figure 4. Comparison of PAN_r (*percentage of urban area needed*) to meet the recommended consumption of vegetables by urban dwellers through UA (target R) with GDP (gross domestic product per capita at purchasing power parity).

densely populated urban areas and for (parts of) cities where the relative economic value of land is lower, an important consideration for policy makers and urban planners.

Second, this study reveals that in many poor countries, space itself severely limits the role of UA in meeting recommended vegetable consumption. Comparing PAN_r with the Gross Domestic Product per capita at purchasing power parity (henceforth 'GDP', used as a measure of wealth; supplementary material SM 2.2) shows that, even though many countries have both low PAN_r and low GDP, poorer countries tend overall to have higher PAN_r than richer countries (figure 4). For example, in the case of Bangladesh, a study for year 2000 estimated that 30% of urban households were involved in UA and that UA contributed to 7% of the national agricultural production (Zezza and Tasciotti 2010); yet our study implies that the country would require more than five times its total urban area in order to provide its urban population with the recommended amount of vegetables (figure 4). Together, these results indicate that while UA is a widespread activity in Bangladesh, achieving vegetable self-sufficiency through UA would be impossible due to an exceedingly high urban population density (the second highest among the 165 countries). While suggesting that UA can meet a larger share of urban vegetable demand in richer countries, our results do not dismiss UA contribution to food security and poverty reduction in developing countries, where the involvement of urban households in UA is often large (Lee-Smith 2010, Maxwell 1995, Zezza and Tasciotti 2010). But the potential of UA to make a *major* contribution to total food availability appears limited in most poor countries where the food security situation is dire: out of the 29 'lowest food security' countries from Yu *et al* (2010) that were included in our study, 23 have $PAN_r > 100\%$ and 12 have $PAN_r > 200\%$.

The third key outcome of this study relates to the role of smaller urban areas as potential, yet-untapped, UA actors. UA is usually associated with large cities like New York, México, or Tokyo, and UA promoters often focus on rethinking large cities in order to inspire people to adopt and develop more sustainable lifestyles (Thibert 2012). However, our clustering analysis shows that small and medium sized urban areas constitute most of the total urban area in the vast majority of countries, as well as globally, and can thus contribute substantially to UA production. Moreover, more than 50% of the world's *urban* population lives in cities with less than 500 000 inhabitants (UN 2004), where UA potential is likely higher due to lower population densities. For all these reasons, UA policies should not focus exclusively on the major urban centers, but should also target smaller urban areas. For example, many UA studies in Tanzania, Kenya and Nigeria (e.g., Adedeji and Ademiluyi 2009, Dongus *et al* 2009, Gallaher *et al* 2013) have heretofore looked at Dar es Salaam, Nairobi and Lagos, respectively, but in these countries small and medium urban clusters actually account for 65 to 85% of the total urban area.

Two important points need to be considered for a better interpretation of our results. First, the *PAN* metric does not offer an absolute ranking of the potential for UA across different countries. In fact, devoting one tenth of urban areas to UA might be feasible with reasonable efforts in some countries, but almost impossible in others. In the case of United States, simply converting a portion of turf grasses (which are implicitly partly included in the MODIS urban dataset) to UA might be sufficient to reach both targets, based on the estimates presented in Milesi *et al* (2005). However, it may very well be more demanding for Germany to reach target A or R, even though both its *PAN* values are similar to the ones of United States. Second, using countries as the smallest unit of analysis leads to average results that mask an underlying heterogeneous reality among the different cities belonging to the same country. For example, a country with *PAN* of 50% is likely to include some cities where less than 10% of the urban area is needed to reach the target, whereas other cities need more than 100%. Nonetheless, we consider that each country-level *PAN* result represents fairly well the distribution of the individual *PAN* values for the different cities within the country (supplementary material SM 2.3).

We assumed that UA is practised on the horizontal extent of urban areas. In recent years, vertical farming—i.e., the hydroponic production of food in artificially heated and lit greenhouses in high-rise buildings—has however received increasing attention as a high-tech and futuristic means of food production (Despommier 2011, Vogel 2008). Vertical farming is based on the idea of growing food on small areas, with very high yields and using advanced technologies, making food production virtually independent from land and soil. We did not explicitly consider vertical farming in our quantitative analyses for two main reasons. First, there is not yet sufficient empirical evidence as to the large-scale feasibility and the actual yields achievable by vertical farming. Second, if vertical farming were shown to be feasible, then the constraint to UA arising from urban space itself would almost disappear. Our study nonetheless provides some relevant considerations about vertical farming. Figure 4 shows that the countries that could potentially benefit the most from vertical farming (i.e., the countries where PAN_r values are the highest) have very low GDP values. These countries are less likely to have the infrastructure, energy supplies and level of technology to adopt and maintain such practices. Conversely, space itself is a much lesser constraint in the richer countries, which may be more enticed to adopt vertical farming.

Finally, various sources of uncertainty affect our *PAN* and clustering analyses. For the *PAN* results, a sensitivity analysis shows that the outcomes are robust to the choice of the UA mix of crops in each country (supplementary material SM 2.4), about which no information was available. We also consider that the other major *PAN*-related uncertainties more likely lead to *PAN* overestimation than underestimation (i.e., the actual space limitation to UA is likely somewhat lower than our results suggest; supplementary material SM 2.5). Unfortunately, the influence of most major uncertainties on *PAN* cannot be rigorously quantified due to lack of appropriate data. In particular, there is currently little evidence against which to evaluate our assumption of UA yields being comparable to rural yields at the global scale. Some studies have observed that UA yields are lower than rural yields due to low soil fertility and soil degradation in urban areas (Enete and Achike 2008), whereas others have found that UA yields can be considerably higher than rural yields due to the use of irrigation, relatively high input levels and the use of good management practices (Altieri *et al* 1999, Duchemin *et al* 2009, Grewal and Grewal 2012). Moreover, our *PAN* results do not explicitly account for the unknown UA-related waste. This limitation may over- or underestimate PAN_a values (depending on whether UA vegetables waste along the food chain is lesser or greater than the difference between FAOSTAT 'food supply quantity' and actual household-level intake), whereas it underestimates PAN_r values (because an actual intake of 300 g/cap/day would require the production of an extra amount of vegetables to account for waste). As for our clustering analysis, the sources of uncertainty we identified do not lead to a clear bias and the final results are robust to changes in the specific procedure we used (supplementary material SM 2.6).

5. Conclusion

In conclusion, we acknowledge that UA is local by nature; hence any attempt to perform a global-scale analysis is bound to include generalizations that are justified and simplifications that can be misleading. Yet we believe that, despite the uncertainties inherent to such an analysis and the missing information on the actual availability of urban area for UA, our study has three main implications that are relevant for policy makers. First, our results suggest that in many countries UA cannot by itself ensure vegetable self-sufficiency for urban dwellers, and even less solve the general problem of food security, simply because the extent of urban area is limited. Second, this space limitation for UA is more serious overall in poorer and more food insecure countries, mostly due to higher urban population densities. Third, UA should also be actively promoted in smaller cities, rather than focussing exclusively on large cities, because smaller urban areas actually comprise the majority of the total urban area. We consider that these outcomes are robust enough to prove worthwhile of consideration by anyone interested in the possible contribution of UA to meet urban dwellers food demand around the world.

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