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Impact of urban form on sunlight availability for urban farming in Asian cities at different latitudes

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1. Introduction

Urbanization process in Asia is increasing at an unprecedented rate. New towns are built in the cities' outskirts occupying farmlands and therefore making urban population more dependent on food produced farer away or from overseas. Increasing local self-sufficiency in terms of food and energy in residential areas is one of the key measures to reduce greenhouse gas (GHG) emissions as well as to mitigate and adapt to climate change. Therefore, the integration of farming areas as part of the urban tissue should be considered as one of the design parameters for new residential districts in Asian cities. However, many factors such as waste management, food safety, pets/disease control, irrigation, distribution, and solar availability have to be taken into account when considering the insertion of farming activities in urban and residential areas. This paper deals with sunlight availability in relation to urban form, density and latitude.

The calculation of solar access according to urban morphology have been the topic of numerous studies to investigate the impact of solar radiation on heating/cooling loads (Wan et al., 2009) and on the potential of energy production with the installation of solar panels and collectors (Kanters & Horvat, 2012). Calculation methods of solar distribution on urban environments and solar access have also being proposed (Ibarra & Reinhart, 2011) and integrated in several urban and building simulation tools. In the context of Singapore, several studies have dealt with the impact of urban form on several environmental indicators like daylight and natural ventilation (Zhang el al. 2012; Lee et al. 2013).

On the other hand, the insertion of farming activities in urban areas have been investigated from the point of view of land use planning (Indraprahasta, 2012), of the use of roof top (Astee & Kishnani, 2010) and of vertical farming and high-tech methods (Despommier, 2013). However, apart from a previous study (Tablada & Zhao, 2014) which analysed sunlight availability and the potential of food and energy production on 25 cases using the point block building typology under Singapore weather conditions, no study was found in literature about the impact of urban form and density on sunlight availability for food production, nor the impact of latitude.

Therefore, the objective of this study is to quantify the sunlight availability in 27 cases with a series of densities and urban morphologies located at three different latitudes in Asia: Singapore (1.3°N), Hanoi (21°N) and Beijing (39.9°N). Local food self-sufficiency are then assessed according to the sunlight requirement for some common species of fruits and vegetables. Two scenarios are considered for urban farming technologies: 'conventional' method of ground-based farming and a 'hybrid' farming method which is a combination of 'conventional' method and 'vertical' farming on the ground and on building facades.

2. Method

The study follows a two-step methodology: (1) the incident sunlight (lux) and daylight autonomy (DA) is calculated on the ground around buildings and on building facades for three typologies and three densities in three latitudes, (2) the food self-sufficiency ratio is calculated considering two farming methods and a limited area for planters on facades.

2.1 Building typology and simulation cases

Three residential typologies are considered in this study. Two of them are typical in East Asia: point block and slab block. A third typology, which is called contemporary, is a simplification of a recent residential typology in Singapore. Contemporary block typology is characterised for having a more irregular shape in comparison with the point and slab block typologies as can be seen in figures 1 and 2.

Each typology is assessed in terms of solar access and daylight autonomy (DA > 10klx) by using a density parameter: plot ratio (PR) (3 similar PRs on each typology: 1.3, 3.1 and 5) and two interrelated geometry parameters: site coverage (Cs) and building height (Hb). PR is defined as the ratio of the gross floor area of all buildings to the area of the analysed plot where all buildings are located. Cs is defined as the ratio of the ground floor area of all buildings to the area of the analysed plot. Hb may vary from case to case but all buildings in the same case has equal Hb. Table 1 shows a summary of the cases and the building indicators considered in this paper for each location: Singapore, Hanoi and Beijing. In total 27 cases were analysed.

The residential area under study is 520 x 520m^2 (27 ha). This represents the equivalent area of a typical large precinct in Singapore or several small ones including the area for car circulation. Figure 2 shows the models used in the simulations for the three building configurations corresponding to the point block typology and three PR: 1.3, 3.1 and 4.9. Figure 3 shows the perspective view of the models corresponding to the slab and contemporary block typologies for the three densities considered. The highlighted areas in both figures represent the analysed area. The surrounding blocks replicates the same morphology in order to account for the effect of neighbouring buildings on sunlight incidence. The sky conditions and the values of solar radiation of the three locations – Singapore, Hanoi and Beijing- are taken from the ASHRAE International Weather for Energy Calculations (IWEC) Data (US Department of Energy, 2013).

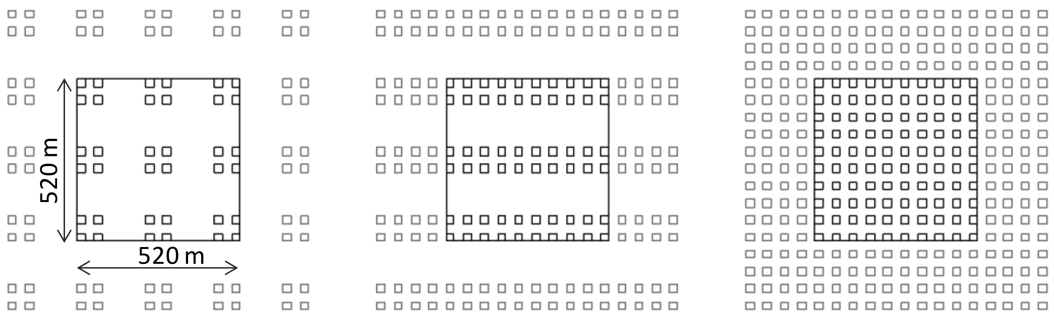

Fig. 1 Schematic of the simulation model for three building dispositions of point block typology corresponding to P-1, P-2 and P-3 cases on Table 1. The framed area is the analysed area.

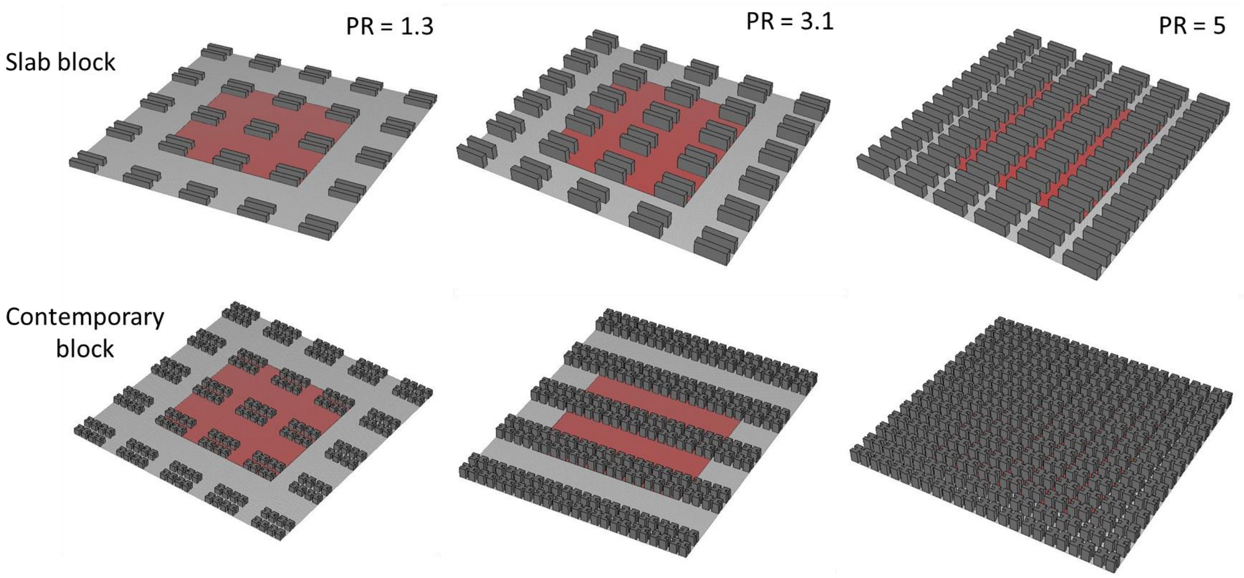

Fig. 2 Perspective view of the simulation model for the slab and contemporary blocks and the three building dispositions considered. The red area is the analysed area.

Table 1. Cases and building indicators

Cases	Typology	Building height (H_b) (m)	Site coverage (C_s)	Plot Ratio (PR)
P-1	Point Block	48	10%	1.3
P-2	Point Block	66	16%	3.1
P-3	Point Block	63	27%	4.9
S-1	Slab Block	24	13%	1.3
S-2	Slab Block	45	18%	3.1
S-3	Slab Block	39	33%	5
C-1	Contemporary Block	21	16%	1.3
C-2	Contemporary Block	36	21%	3
C-3	Contemporary Block	36	35%	5

3. Settings and calculation method

3.1 Sunlight availability

Sunlight access –illuminance levels (lux)– on the ground and building facades were calculated by Daysim (version 3.1b) (Reinhart and Walkenhorst, 2001). Details of the simulation settings are given in Tablada & Zhao, 2014. Daylight Autonomy (DA) was also calculated on each point of a grid (lighting sensors) on the ground and facades for the whole year from 8:00 till 18:00. DA is a climatic-based index which denotes the percentage in which a minimum –defined by user- illuminance level is achieved by daylight alone for a specific time interval (Reinhart and Walkenhorst, 2001). DA is used in this paper to determine the percentage along the whole year in which each analysed point receive more than 10 000 lux during day time. The optimal illuminance level for certain vegetables and fruits is considered to be 10 000 lux for about 8 hours (Conover and Flohr, 1996). When the DA is below 80% (less than 8 hours with 10 000 lux), a reduction coefficient is applied for the calculation of the annual yield.

Model simplifications have to be introduced in order to reduce calculation time. One of such simplifications was to consider the effect of the shading devices – 4% lees sunlight on ground surface and 12% less on facades– by applying an equivalent reflectance coefficient (-20%) on the facade to account for the ground illuminance reduction. However, since the facade reflectance values have little impact on the facade illuminance levels, another coefficient is applied directly on the final illuminance levels to account for the presence of horizontal shading devices. Considering overhangs of 30cm, a coefficient accounting for a 10% reduction is applied.

3.2 Population and area for farming

The amount of population per case is calculated according to the typical floor area distribution and minimum area per person in Singapore's public housing and precincts. Therefore, no variation in this matter was considered for the cases of Hanoi and Beijing in order to clearly identify the effect of the latitude on food self-sufficiency. In each precinct 70% of gross floor area (GFA) is considered residential, 20% institutions and 10% commercial. The total amount of residents per case were calculated according to the average area per capita in the HDB of the last decade equal to 25m^2 and considering a floor plan efficiency (rental flat area out of GFA of residential building) equal to 85%. For the farming activity we consider part of the ground area and part of the facade. The farming area on the facade considers 50 cm of planters along 30% of the perimeter of the facade. The other 70% of the facade perimeter is considered to be used for the installation of Building Integrated Photovoltaic (BIPV) panels. More details about the ground and facade arrangement can be found in Tablada and Zhao, 2014.

3.2 Selection of crops and food self-sufficiency

A selection of crops was done in order to calculate the yield potential of the farming areas and the potential of food (vegetables and fruits) self-sufficiency for the total population in each case. The criteria to select the type of crops were (1) suitability for local context, (2) preference among local residents and, (3) productivity. Although the selection was based on information collected in Singapore, due to common cultural affinities, same type and proportion of fruits and vegetables are considered for Hanoi and Beijing. They are: Kang Kong (30%), Water Mimosa (20%), Chinese Celery (20%), Water Cress (10%) and Pumpkin (20%); the fruits are Dragon Fruit (80%) and Banana (20%).

Two farming scenarios are considered: 'conventional' and 'hybrid'. Conventional method considers both the traditional ground soil gardening and the use of soil planters or containers. Hybrid method is a combination of the 'conventional' and the 'vertical' methods (50% ground surface each). The 'vertical' method refers to hydroponics, aeroponics and vertical structures. The vertical methods are considered to be around 4 times more productive than the conventional ones (Mugundhan et al., 2011). Only vegetables are considered to grow using the 'vertical' method.

4. Results

A summary of the results regarding sunlight availability on ground and facade surfaces and the food self-sufficiency ratio for the three typologies and the three locations are shown in this section.

4.1 Sunlight availability

Figure 3 shows the average of DA (illuminance levels >10 klx) of the three typologies for the ground and facade surfaces. As expected, there is a clear negative correlation between density and sunlight incidence, having the cases with PR = 5 the lowest DA per location. The illuminance values are also higher on the ground than on the facades disregarding the density or the location. Regarding the effect of latitude on sunlight incidence, the main difference is between the cases of Hanoi with respect to Singapore, especially for the cases with the highest density PR = 5. The lower sunlight incidence in Beijing with respect to Hanoi are smaller than expected and for PR = 1.3, the DA is slightly higher in Beijing for the point block and slab block typologies than in Hanoi. Moreover, the decrease of DA due to higher latitude is more evident on facades (-20% avg) than on the ground surfaces (-10% avg), especially for the highest density (PR = 5).

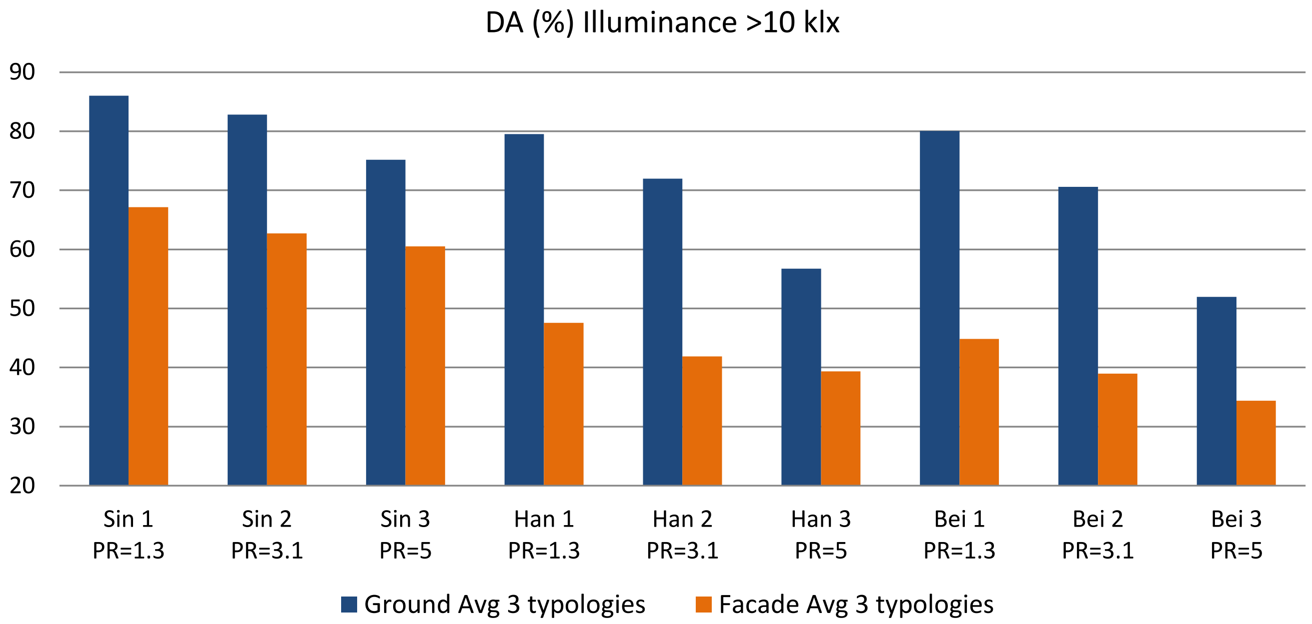

Fig. 3 Average of DA (illuminance > 10klx) of three typologies for the ground and facades.

Regarding sunlight incidence according to facade orientations, a different pattern is observed among the three latitudes as shown in figure 4 for the cases with PR = 3.1. The differences among the facades are less important for Equatorial latitudes (Singapore) due to the relative higher position of the sun throughout the year and the seasonal solar incidence both on the north and south facade. On the other hand, the differences between DA on the north and south facades increases with higher latitudes. The differences among the three typologies are insignificant (ΔDA 1-2%) for the same facades. Larger differences are obtained among the three densities (<10%) for the three typologies except for east and west orientations on the contemporary block typology (around 15%) between the lowest and mid density.

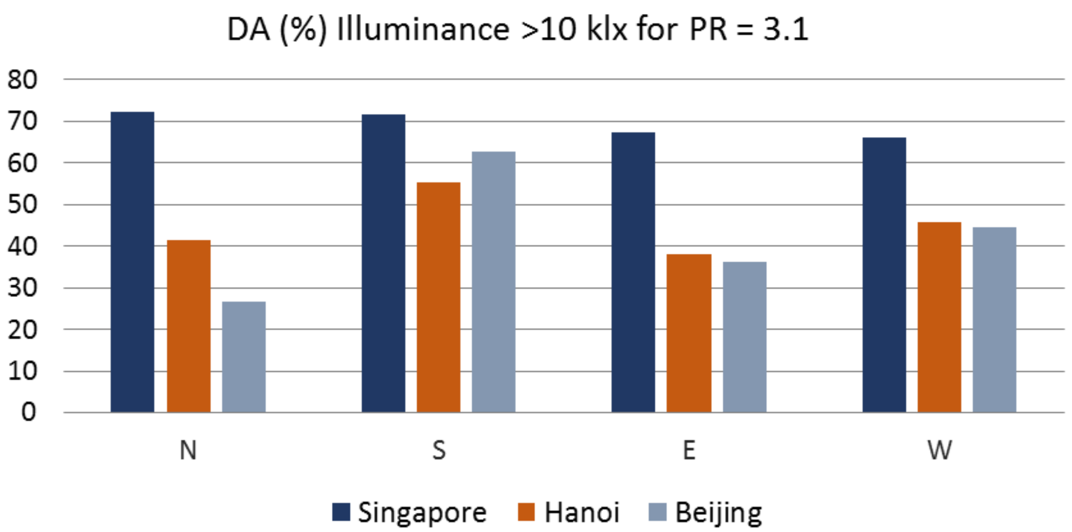

Fig. 4 Average of DA (illuminance > 10 klx) of three typologies for PR = 3.1 and the four facade orientations.

4.2 Food self-sufficiency

Figure 5 shows the ratio of food (vegetables and fruit) self-sufficiency for the 27 cases analysed when the hybrid farming method is used, which achieve about 1.4 times higher production than conventional method according to the terms of this study. The pattern for the three locations and the three typologies is very similar. There is a drastic reduction (60-70%) of food self-sufficiency when density increase from PR=1.3 to 3.1. Similar relative reduction is observed when density increase from PR=3.1 to 5, however that reduction is smaller in absolute terms. Regarding the influence of the building typology, point and slab block typologies allow slightly higher food self-sufficiency than contemporary block typology especially for Hanoi and Beijing cases.

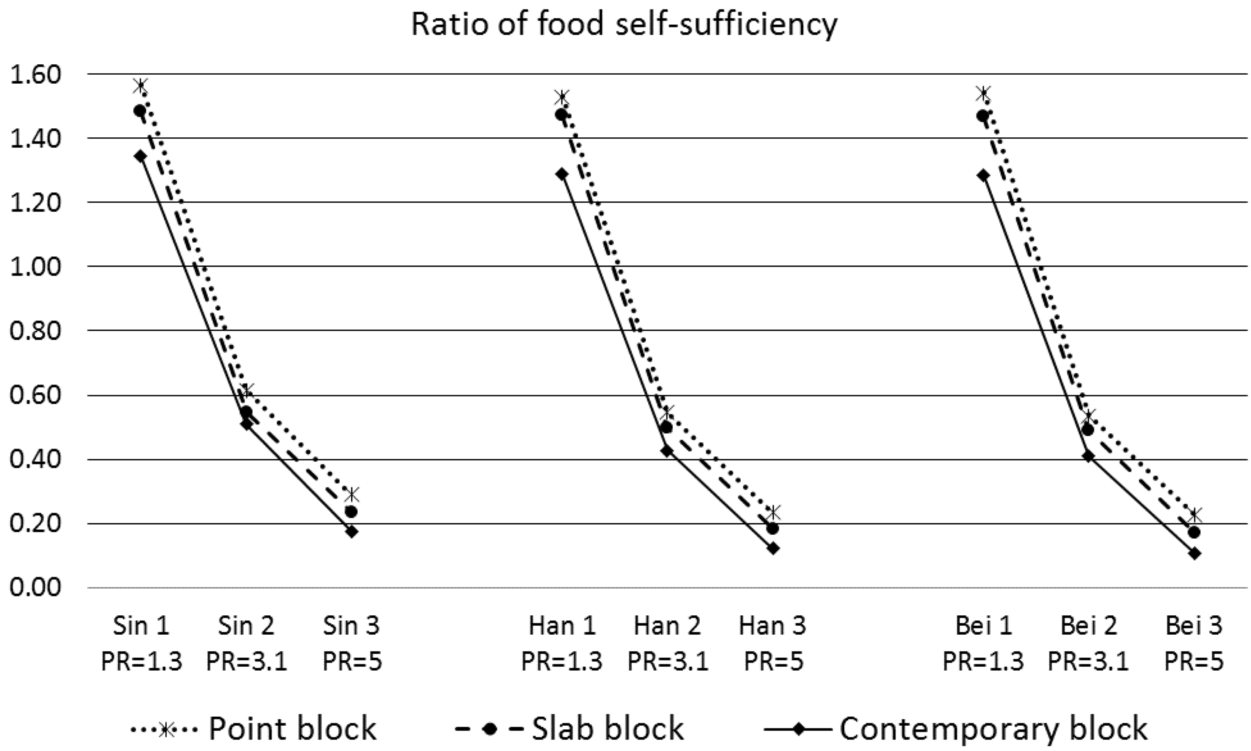

Fig. 5 Ratio of food self-sufficiency on three locations.

Similarly to the analysis of DA, the effect of latitude is smaller than expected when analysing food self-sufficiency, especially when comparing the results from Beijing with those from Hanoi. Table 2 shows the relative differences between the cases from Hanoi and Beijing in comparison with the cases from Singapore and Hanoi respectively. The reduction of food self-sufficiency of the cases from Hanoi with respect to Singapore is larger than the reduction from Beijing with respect to Hanoi cases even though the latitude difference among the three locations are similar (about 19°). For the lowest density, there is even a slightly increase of food self-sufficiency for the point block typology in Beijing with respect to Hanoi.

Table 2. Food self-sufficiency reduction (%) according to latitude: Hanoi vs. Singapore and Beijing vs. Hanoi

	Hanoi vs. Singapore			Beijing vs. Hanoi		
	PR=1.3	PR=3.1	PR=5	PR=1.3	PR=3.1	PR=5
Point Block	-3.6%	-6.9%	-5.7%	1.2%	-1.1%	-0.6%
Slab Block	-1.5%	-5.1%	-4.9%	-0.2%	-0.5%	-1.3%
Contemporary Block	-5.5%	-8.3%	-5.4%	-0.4%	-1.6%	-1.5%

5. Discussion and conclusions

This paper summarise the process and results of the calculation of sunlight incidence on the ground and facade surfaces and well as the prediction of Daylight Autonomy for illuminance values higher than 10 klx in order to evaluate the potential food self-sufficiency of 27 cases with three typologies and different densities in cities located on three latitudes: Singapore (1.3°N), Hanoi (21°N) and Beijing (39.9°N).

Results show that the impact of density on sunlight availability is evident in all latitudes. However, that impact is lower for equatorial than for higher latitudes. In addition, the reduction of DA for food production in the latter case is more evident on building facades than on the ground due to the obstruction of surrounding buildings when density is high.

The influence of facade orientation was also analysed. As expected, the façade orientation is less important on lower latitudes than on higher ones thanks to a sun path closer to the zenith which evenly distribute solar access throughout the year not only on the east and west, but also on the north and south facades. On the other hand, the reduction of DA on the facades of Hanoi and Beijing cases due to higher density is more important on the north façade (for North Hemisphere) and it is somehow counterbalanced with a less critical DA reduction on the south facade.

The sunlight availability and therefore the potential of food self-sufficiency is more affected by the factor of density, then by typology and lastly by latitude. Part of the cause of the minor impact of latitude on food self-sufficiency, especially when comparing the cases of Hanoi and Beijing, is the sky conditions. Although the average global radiation from 8.00 to 18.00 is higher in Hanoi (366 W/m2) than in Beijing (341 W/m2), the direct solar radiation is higher in Beijing (not considering the effect of pollution) (302 W/m2 vs 238 W/m2). This increases the number of hours in which illuminance levels in Beijing are higher than 10 klx in comparison with Hanoi. However, in locations with similar latitudes but with clearer sky conditions than in Hanoi (e.g. Havana, 23.2°N) larger differences are observed with respect to Beijing, especially from January till March.

Another reason for the minimized effect of latitude is the 'underutilized' amount of sunlight on latitudes near the equator due to the planter area and location proposed in this paper. Equal planter distribution (30 % of facade perimeter) and type of vegetables were conceived in this study disregarding the latitude in order to reduce the number of variables and for achieving a fair comparison among the cases. The other two thirds of the façade perimeter were assumed to be PV panels acting as shading devices. Therefore, the potential food production on latitudes near the Equator can be maximized by the use of more intensive farming methods and the installation of denser planter systems on building facades without affecting daylight conditions inside apartments. A possible integration of both farming –on balcony's railing or windows– and solar panels –substituting overhangs– could maximize the area of the façade for food and energy production and could more efficiently use the 'surplus' sunlight (> 10 klx). On the other hand, the DA reduction on higher latitudes could be offset if the amount and distribution of planters better corresponds with the uneven sunlight incidence between and on each facade.

Overall, the study showed the importance of density when considering solar energy to produce food, as well as any other renewable resource. It also provides the basis for the elaboration of general and particularized guidelines in terms of density and urban form to achieve the required sunlight for the integration of farming areas in cities at different latitudes. Efficient integration between farming and solar panels will also be explored. For that aim, new series of simulations on cities with different latitudes but more similar sky conditions will be performed.

Acknowledgment

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