Planning Urban Food Production into Today's Cities

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Abstract

If cities are to become more sustainable and resilient to change it is likely that they will have to engage with food at increasingly localised levels, in order to reduce their dependency on global systems. With 87 percent of people in developed regions estimated to be living in cities by 2050 it can be assumed that the majority of this localised production will occur in and around cities. As part of a 12 month engagement, Queen's University Belfast designed and implemented an elevated aquaponic food system spanning the top internal floor and exterior roof space of a disused mill in Manchester, England. The experimental aquaponic system was developed to explore the possibilities and difficulties associated with integrating food production with existing buildings. This paper utilises empirical research regarding crop growth from the elevated aquaponic system and extrapolates the findings across a whole city. The resulting research enables the agricultural productive capacity of today's cities to be estimated and a framework of implementation to be proposed.

Introduction

The future possible impacts of technological food systems within todays cities are at present difficult to assess. The aim of this paper is to devise a method of analysis in order to determine the agricultural productive capacity of a Northern European city ratified through the use of real-world data on technical food systems. This data was collected from an operational elevated aquaponic system in Manchester, England designed and constructed by Queens University Belfast. The paper discusses the benefits of integrating agriculture within buildings and cities and analyses its impact on total domestic food production; the environmental benefits associated with this; and the resulting economic impact such activities could have on buildings, neighbourhoods and cities.

The ecological context of food in the UK

Self-sufficiency and food

The UK, like many other developed regions, is dependent upon food imports to sustain its population. In 2006 the UK spent £6 billion on importing fruit and vegetables alone and is reported to be 'about 60 percent food sufficient' (The Cabinet Office, 2008), leaving a 40% food deficit which has to be import from other countries. Over the past six years, the debt of the UK as a percentage of GDP has doubled from 42.8 percent in 2007/2008 to 84.3 percent in 2013, which equates to a gross debt of £1.387 trillion (Office for National Statistics (ONS), 2013). As a result, the food supply chain upon which the UK depends on is economically fragile, susceptible to change without warning, and ill

equipped to deal with shock. These figures, however, only take into account the economic strain of supplying the UK with food. The feeding of the UK population also has an environmental impact.

Taking into account nourishment, shelter, mobility, goods and services the ecological footprint of the UK is estimated to be three times its size, requiring 321,621,000 global hectares to sustain its population (Stockholm Environment Institute (SEI), 2003). This impact corresponds to 5.45 global hectares per capita, which is in striking contrast to the fair land share per capita of 1.8 global hectares (World Wide Fund for Nature, 2012). This dictates that the UK's ecological footprint needs to decrease by at least 65 percent in order to live in equilibrium with the replenishment of natural resources. Nourishment, as a proportion of the overall ecological footprint, accounts for 28 percent of the total impact of the UK, requiring nearly 92 million global hectares (SEI, 2003). In 2008, the food industry accounted for 18 percent of the total CO_2 equivalent production in the UK, estimated at a total of 147 million tonnes per annum (The Cabinet Office, 2008). The transport of food within the UK produces 19 million tonnes of CO_2 and burns 20.9 million tonnes of oil per year (The Cabinet Office, 2008). If every person on the earth lived as one did in the UK, three earths would be needed in order to supply the demand indefinitely.

Food waste and land use

In 2011, the world's population surpassed 7 billion people for the first time in human history (Economic and Social Affairs division of the United Nations (ESA), 2013). As a result, the availability of agricultural land per capita is decreasing. In 1970, 0.38 hectares of global agricultural land was available per person. This value decreased to 0.23 hectares in 2000, and is projected to decline to 0.15 hectares per capita by 2050 (Food and Agriculture Organisation of the United Nations (FAO), 2012). A single hectare of agricultural land will, by 2050, have to supply enough food for 6.7 people annually, whereas the same area of land in 1970 only had to produce enough food for 2.6 people. It is a possibility, that by 2050, this agricultural land may become exhausted and be incapable of supporting the intensive agricultural activities needed to feed the 10 billion world.

The availability of food, however, is only part of the

problem facing future populations; waste is also a concern. The Food and Agricultural Organisation of the United Nations reports that 28 percent of global arable land is used annually for the production of food that is either lost or wasted (FAO, 2013). Within the UK this food waste equates to approximately 16 million tonnes per year at a cost of £22 billion per annum (Waste & Resources Action Programme, 2011). The UK is, in essence, paying to waste food, waste energy, and damage the environment unnecessarily through the intensive industrial activities which are needed to feed its populations.

The wasting of food also has social and humanitarian impacts. It is estimated that 12 percent of the world's population is undernourished at a figure of approximately 842.3 million people (FAO, 2013). Taking into account that 28 percent of all food produced is either lost or wasted, world hunger could be solved twice over if a solution could be brokered.

The actions needed to prevent any further ecological deterioration as a result of the intense industrial activities needed to feed the UK, as well as address the issues surround food security, lay in the ability to produce more food domestically, in addition to wasting less. However, these actions are in no way simple. The Office for National Statistics notes that 69 percent of UK land is already utilised for agriculture, with 11 percent of land developed, 11 percent as forest/woodland and the last 9 percent left to other natural habitats (i.e. grassland, mountains, moors, coastlines and marine environments) (Office for National Statistics and East Anglia University, 2010). The need to produce more food when there is little to no additional land available makes the goal of producing more food difficult.

By 2050 the urbanised population of the planet is expected to reach 67.2 percent; accounting for 1.1 billion people in developed regions and 5.1 billion people in less developed regions (ESA, 2013). If cities are to become more sustainable and resilient to change it is likely that they will have to engage with food at increasingly localised levels. With 87 percent of developed regions estimated to be living in cities by 2050 it can be assumed that the majority of this localised production will occur in and around cities, and more specifically, within or upon buildings.

Soil-less growing technologies

Background to the technologies

Nearly all food today is grown in soil but within urban areas, and more importantly within or upon buildings, soil-based agriculture may not be the best method. This is due to the large proportion of contaminated land in many urban areas - a byproduct of the industrial revolution - as well as its additional weight, which adversely affects its ability to be retrospectively added to buildings. Thus, localised food production within cities depends upon alternatives to soil based practices. One such alternative is to use technical food systems. These hybridised systems, utilising technical products such as glass, plastic, and mechanical pumps, allow food to be grown directly in nutrient rich water at a fraction of the weight.

There are two recognised methods in which food can be grown within technical food systems. These include hydroponics and aquaponics. These techniques utilise similar equipment in order to grow food, but the way in which they make nutrients available to crops is very different. Hydroponic systems utilise nutrients that are added manually to a recirculated water system, whereas aquaponics aims to develop an ecosystem between fish and crops. Aquaponic systems are dependent upon the naturally occurring nitrogen cycle to make nutrients available to crops. The system utilises waste ammonia (NH_3) - produced by the fish as a byproduct of respiration - and through the natural colonisation of nitrosomonas and nitrobacter bacterias within the system, converts the waste ammonia primarily into nitrite (NO_3) and later into nitrate (NO_2). This conversion serves two functions. Ammonia is toxic to fish it would poison them if allowed to accumulate within the water supply. The second function of this process is that nitrate is an available form of nitrogen - a plant's largest nutrient requirement - which crops can easily take up across the surface of their roots. The fish, bacteria and crops live symbiotically, much as they would within a natural ecosystem.

In both hydroponics, and aquaponics, crop roots are in direct contact with the nutrient rich water. As such, the crops use little effort in acquiring nutrients and can instead, utilise a larger proportion of their energy to grow. As a result, yields are substantially increased (in some cases up to four times) and water use is reduced by a factor of up to ten when compared to traditional agriculture (Bernstein, 2011). Through the growing of crops indoors or under glass, a protective environment is created which increases resilience to shock events such as storms, prolonged rainy periods, temperature drops or dry spells. Their reduced weight, through the use of Nutrient Film Technique (NFT) - a growing channel utilising only a few centimetres of water - allows such systems to be successfully retrofitted into or onto existing buildings without compromising the building's structural integrity.

The design of a novel roof-based aquaponic system

As part of the Manchester International Festival 2013, Queen's University Belfast was approached to design and implement an elevated aquaponic food system within a disued mill in

Figure 1: Aerial view of the elevated urban farm in Manchester, England (left) with rooftop NFT system (right)

Figure 2: Internal view of the urban farm in Manchester, England.

Manchester, England (Fig. 1). The project itself was a 12 month engagement and included the design, construction and commissioning of one of the very first elevated farms within the UK.

The system was partially contained within the building and partially upon the roof, where light levels were highest. The more visually engaging components of the system were contained on the top internal floor of the building. This included fish tanks, a filtration/mineralisation system, and deep rooted crop bags placed in the south-facing windows (Fig. 2). The roof space housed the NFT system - located within a large polytunnel - capable of growing 4,000 leaf crops at any one time. The design team worked closely with structural engineers throughout the course of the design and construction of the systems to ensure it would not compromise the existing structure of the mill. As a

result, the heaviest elements of the system (i.e. fish tanks and polytunnel) sit upon primary beams in order to safely distribute the load to the ground.

In total there are 12 fish tanks, which are fed with filtered, clean, fresh water returning from the roof as a result of bacterial and crop filtering actions. The overflow from the fish tanks collects in a sump, and the water is pumped to the filtration/mineralisation bank where it drains consecutively through a series of siphonic containers comprising of expanded clay balls and worms. The expanded clay balls provide the large surface area needed upon which nitrifying bacteria can colonise, with the worms helping with the breakdown of solid waste. When the water is nitrogen rich and free of solid waste it is pumped toward the silicon bags hanging in the south facing windows. These deeper grow bags cultivate plants such as tomatoes and peppers, which require sig-

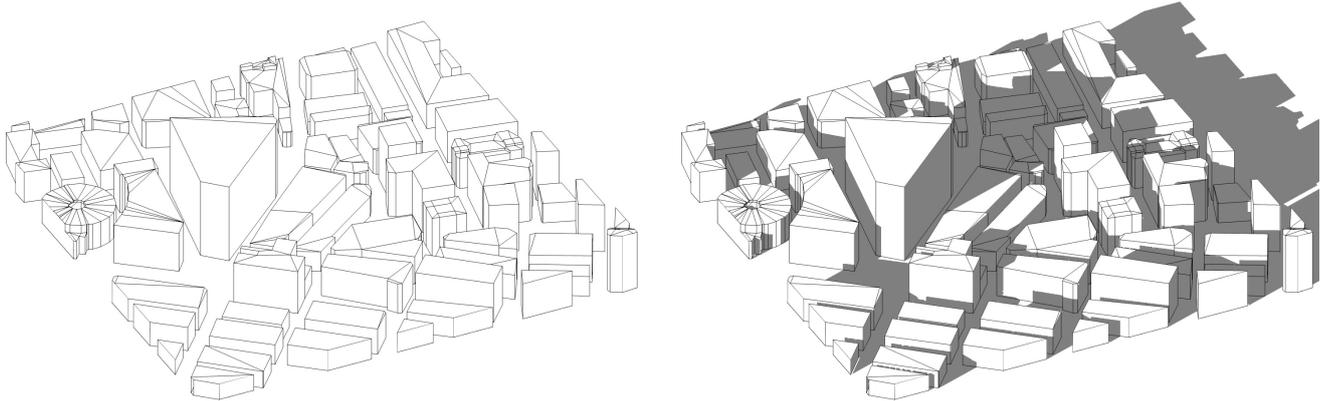**Figure 3**: Facade Farm prototype

Figure 4: A section of the three-dimensional model (left) with sample image of shadow information (right)

nificantly larger root systems in order to grow. The water is lastly pumped up to the roof and into the polytunnel where it flows down through 34 NFT channels, each 14m in length, in order to grow leaf crops (Fig 1). The clean filtered water flows back down to the fish tanks, where the process can start again.

The NFT system was capable of growing 26.66 crops/m2, including the additional space taken up by filtration, fish tanks and walk ways between crops. Based on a growing season of eight months, consisting of four harvests, the system is capable of producing up to 16,500 crops per annum. The sale of the crops in the local shop as part of the project sold for between £2 and £4 per crop dependant on size and species of crop. Hence, the system could generate between £33,000 and £66,000 per year. The material cost of the system itself was approximately £30,000 with an additional £30,000 spent on labour. The system was designed to need only one person to operate it on a day to day basis and a full operational manual was produced by Queen's University Belfast upon the hand over of the system to the building tenants.

Although the aquaponic system and urban farm was successful, it was clear upon completing the project that it may not necessarily be good practice or cost effective in future to locate these systems within buildings. They not only take up space within structures that could otherwise be utilised for office or residential purposes, generating income, but they also create issues related to flooding and water ingress from open water systems - i.e. a mixture of pressurised and unpressurised plumbing. Containing technical food systems within buildings also greatly reduces the amount of light available

for crop growth. Deploying these systems on the external skin of buildings - i.e. rooftops and facades - in the future would eradicate both of these issues in addition to freeing up the floor plan of buildings for commercial or residential activities.

Facade Farm Prototype

The benefits associated with exterior systems led to the development of the 'facade farm' prototype: a twin walled glass facade, capable of growing crops within its cavity. The vertical surfaces of architecture, which generally experience too much glare or too much heat gain, would be the perfect sites for the growing of plants, which in turn would reduce both glare through foliage and heat gain through transpiration, decreasing building energy consumption and creating economic return through the sale of crops.

The first constructed facade prototype took all the available research from the larger aquaponic system, which occupied a whole building, and miniaturised it into a space 3m high, 2.5m wide and 35cm deep (Fig. 3). This space housed all the components seen within the larger system, including fish tanks, filtration/mineralisation unit, and growing channels. The prototype of the facade farm was capable of delivering 15 crops per metre squared of vertical surface, taking into account the space required for fish tanks and filtration. The prototype cost approximately £7,500 minus labour and using the sale value of the crops sold in the adjacent shop, is cable of producing approximately 450 crops per year (60 crops/m2/annum).

The Agricultural Capacity of Cities

Cities can reduce their ecological footprint and positively affect their impact on the earth through the integration of urban agriculture upon their abundant surface area. However, not all surfaces within a city are capable of supporting the growth of crops due to orientation and/or overshadowing. A virtual modelling methodology - one that views cities as illuminated surfaces - is necessary so that the productive capacity of a city can be quantified, and the impact on domestic food production be calculated. The following analysis describes a methodology where direct light falling upon a surface is captured through the use of a three-dimensional model, and the aggregated annual lighting data used to help predict the total annual crop production of a city.

For the purposes of this paper, the city centre of Manchester, England was used as a case study to help derive and test the method of analysis. The main reason for this choice is the close proximity of the centre of the city to the elevated aquaponic system used for productive assessment. The centre of the city lies upon an area of land approximately 369 hectares in size, although its total surface area is closer to 720 hectares. This implies that through the building of structures the surface area of the city has doubled in size. The following analysis strives to determine to what extent this additional surface area is capable of supporting crop growth and hence, help inform a future framework of integration for urban agriculture within the city itself.

It should be noted that the research understands that availability of light is only one aspect effecting the integration of urban agriculture within existing cities. Other issues include the access to the right skills, ownership of urban surface, as well as the inclination of inhabitants to grow food. However, the point is taken that this method of analysis would be used at a city level, to discuss such possibilities with local authorities and to identify which areas might be suitable for pilot studies. Upon which, more detailed site analysis regarding applicability can be taken forward.

Three-Dimensional Modelling
To make it possible to determine upon which surfaces of the city crops can be grown, the overshad-

owing of each horizontal and vertical surface must first be visualised and understood. This is achieved by creating an accurate three-dimensional model of a particular city within virtual space onto which virtual light rays can be cast.

To create the virtual model of Manchester more than 2800 building plots were created in three-dimensional space, with each plot containing information on building form and building height (Fig. 4). Both of these characteristics are crucial in determining the overshadowing, and therefore reduction in light capture, as a result of adjacent buildings. All building plots were modelled simply and therefore were all represented as having flat roofs. In later analysis, all pitched roofs are identified and omitted from the analysis due to the lack of data regarding the growing of crops on an inclined plane. However, these surfaces may be utilised for solar energy capture in the form of photovoltaics or solar hot water which could help operate the technical food systems upon adjacent roofs and facades. The data used to create the virtual model of Manchester was taken from Land Map (*www.landmap.ac.uk*), which identified the height of each building plot above ground level. This data is referenced by Land Map as originating from Cities Revealed which is now part of the Geo-information Group.

Modelling Light Intensity and Assessing Shadow Data
Once the model of the city in question has been created in three-dimensional space it is then capable of accepting light rays in order to generate accurate shadow maps.

To collect the shadow information, a physical sun object was added to the scene, which is dependent upon latitude, longitude, time of day and month of year to calculate the sun's position. The latitude and longitude used for Manchester was 53°29'N 02°12'W. Using this object, images were taken at half hourly intervals from sunrise to sunset to represent a typical day within each month. The 21st day of each month was used to represent a 'typical day' within the study, due to the winter and summer solstices occurring on the 21st of December and 21st of June respectively.

To better represent the three-dimensional data as two dimensional images, the analysis splits the in-
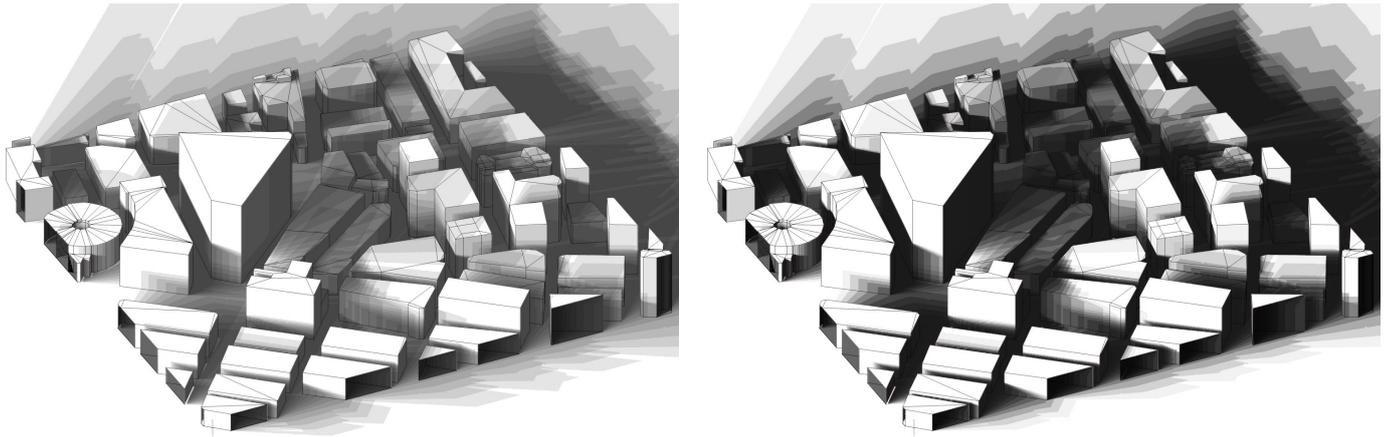
Figure 5: Multiple shadows with the same transparencies (left) and with accurate transparencies applied (right)

formation into vertical and horizontal data sets. To collect these two data sets three views are utilised in order to better represent the findings. The light capture of the horizontal surfaces - i.e. roof spaces - is viewed from above in plan so as to clearly view each individual roof. In contrast, the vertical data - i.e. building facades - is difficult to represent as a single image. Therefore, two views with different vantage points were utilised in order to fully understand the light capture of the vertical surfaces. These views were taken from the south-east and the south-west at an elevation of 60 degrees and in parallel projection. For the facade study, no data was captured from north facing surfaces as it could be assumed that these surfaces would be over-shadowed for the majority of the day and would only receive diffused radiation.

In total, over 250 images were taken to represent each half hourly shadow across a single day within each month of the year (Fig. 4)

Creating Shadow Maps

To create the shadow maps, the individual shadows for each respective month were overlaid on top of one another and a transparency applied to them in order to create a gradient map. Where multiple shadows coincided, darker patches would be seen, and areas mostly out of shadow would be represented as lighter patches (Fig. 5). However, this approach does not accurately represent the impact of a single shadow upon the daily solar capture of a surface throughout the day. That is to say that an area in shadow at midday would see a greater decrease in its overall daily light capture, than an area only in shadow during sun rise or sunset.

In order to account for this the impact of each shadow was individually calculated. This was achieved by calculating the proportion of total daylight that

Figure 6: Completed roof top shadow map for March (left) and completed south-east facade map for June (right)
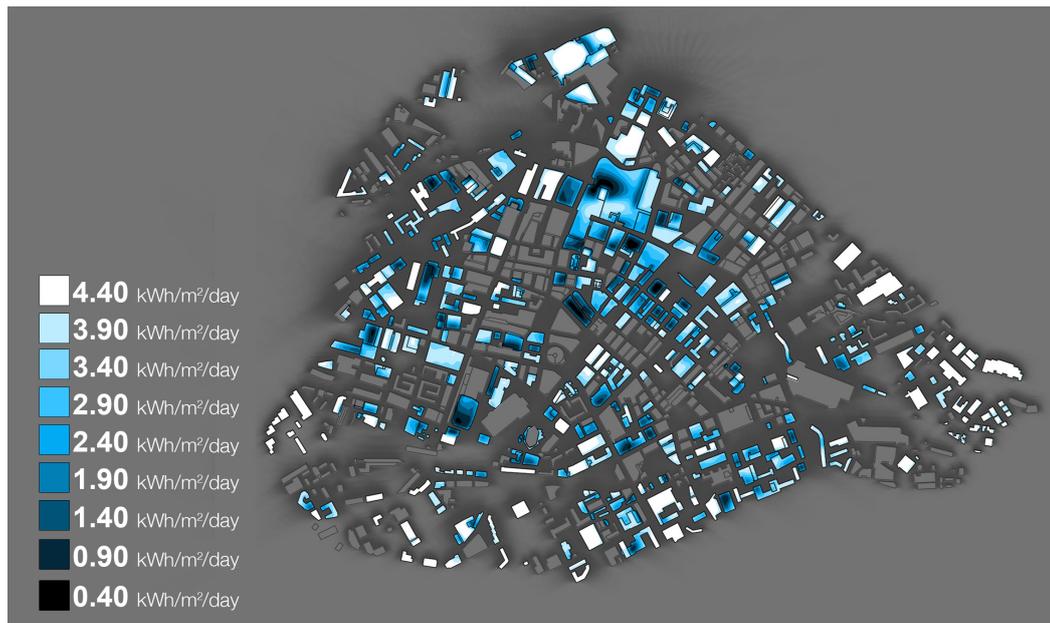
Figure 7: Annual roof top shadow map

landed upon a surface within each half hourly period against the total light capture of a known day. Taking April as an example, the light falling upon a surface between 13:00 and 13:29 accounts for 6.2 percent of its total daily light capture, whereas the light falling upon a surface between 07:00 and 07:29 accounts for only 0.4 percent of its total light capture. Therefore, a surface in shadow between 13:00 and 13:29 would see a reduction in it total daily light capture of 6.2 percent and a surface in shadow between 07:00 and 07:29 would only see a 0.4 percent reduction in its daily solar capture. Hence, shadows towards the middle of a day have a larger impact on the overall light capture of a surface and should be represented as darker than shadows towards the extremities of the day. Once calculated, the transparencies were amended to reflect this, representing the data more accurately than before (Fig. 5). The final stage of producing the shadow maps was to combine the shadow information with accurate lighting data. The data, kindly provided by SolarGIS, captured information on both direct irradiation (i.e. direct sunlight) and diffused irradiation (i.e. diffused light from the sky). An area in continual shadow would only ever receive diffused irradiation from the sky, whereas an area in constant sunlight would always be exposed to the total direct irradiation value. Taking the lighting data for March as an example, it can be seen that the total direct irradiation is 2.18 kW/m2/day and the total indirect illumination

is 1.40kW/m2/day. Therefore, it can be assumed that all areas that are a solid black within the shadow map (i.e. always in shadow) would have a light capture of 1.40kW/m2/day whereas the areas without any shading would achieve a light capture of 2.18 kW/m2/day. The resulting images clearly represent which roofs and facades are susceptible to overshadowing, and how much energy each surface receives throughout the day within each month (Fig. 6).

Upon the completion of the shadow maps it was important to identify pitched roofs and eliminate them from the research. If Manchester was to be comprised entirely of flat roofs, it would have a total roof area of 136.3 hectares. However, 44.2 percent of the buildings have pitched roofs leaving the remaining flat roof area at 76 hectares.

Average Annual Light Capture
To determine the overall capacity of the horizontal and vertical surfaces to produce food, the average annual light capture would also be required. In order to combine all the overshadowing data into an annual shadow analysis, the yearly impact on light capture for each shadow had to be calculated. This was achieved by calculating the proportion of total daylight that landed upon a surface within each half hourly period of a specific day, against the total light capture of a total year. Thus, providing a percentage contribution of each half-hourly

section to the total yearly light capture of the city.

For example; the light capture of a surface in shadow between 10:00 and 10:29 of a typical December day is reduced across the year by 0.1 percent. If a surface is in shadow between 12:00 and 12:29 in June, its light capture is decreased by 0.9 percent across the year. When all 258 shadows are laid upon one another, and the yearly transparencies of each shadow applied, an annual lighting map emerges. A stepped gradient was added in order to reduce the number of colour shades within the image and to allow a clearer differentiation to be drawn between well lit and poorly lit areas (Fig. 7). The annual shadow map covers a much larger range of values than previous monthly lighting information and, as such, is divided into nine 0.5kWh/m2/day energy levels. The annual results were processed in blue to help differentiate the data from the monthly data.

In order to determine what relevance this data has on annual crop growth, the energy needed by a plant for photosynthesis to occur must be included in the research. As a working average some plant species require a minimum of 1MJ/m2/day (0.28 kWh/m2/day) of light energy to survive. To obtain maximum growth rates, however, they require 3MJ/m2/day (0.83kWh/m2/day) (Badgery-Parker, 1999). In order to maximise the integration of technological food systems, the saturation point of photosynthesis (i.e. 0.83kWh/m2/day) will be taken as the baseline from which crops can be grown in a city to achieve the highest yields.

Predicted productivity

If every flat roof of the total 76 Hectares was capable of growing crops, Manchester could grow approximately 20.2 million crops at any one time based on 26.66 crops/m2 as found in the elevated aquaponic system. Extrapolating this throughout the year, based on a two month growing cycle for eight months of the year, Manchester would be capable of growing close to 81 million crops per annum. Based on a sale price of between £2 and £4 (as per the sale values achieved from the food shop adjacent to the elevated aquaponic system), the resulting crop could be worth between £162 million and £324 million per annum. Using the annual lighting data above, all areas indicating a yearly average

light capture of 0.9kWh/m2/day or above would be considered perfect sites on which to grow food. However, once these sites are identified further research would be needed to conclude the viability of urban agriculture dependant on access, structural integrity and the inclination of the building owner to partake in such activities to name a few.

In the case of Manchester, 99.4 percent of available flat roof surface is capable of supporting crop growth and therefore, the total growing capacity of city centre roofs in Manchester is 80.4 million crops (based on four harvests per annum) indicating a total worth of between £160.8 million and £321.6 million per annum based on a sale value of between £2 and £4 per unit.

In total, the area of vertical facade accounts for 310.6 hectares of the total surface area of the city. Based on the information collected from the facade prototype - that facades can produce up 15 crops per metre squared of vertical surface - the vertical surfaces of Manchester are capable of growing 46.5 million crops at any one time. However, approximately 20 percent of the entire facade area is incapable of supporting crop growth due to close proximity of other buildings (i.e down tight streets or alley ways) with a further 35 percent of the facade area facing between North-East and North-West, never receiving any direct sunlight as a consequence. Although capable of supporting plant life during the brighter and warmer months, for the purposes of this research, the north facing facades would be collectively titled 'additional growing space' due to their orientation. The east, south and west facades would be more effective at growing crops. Therefore the overall productive area of vertical surfaces is 167.7 hectares, not including the 86.9 hectares of north facing facades. Using this area to grow crops in double skinned facade farms would enable a total of 25 million crops to be grown at anyone time. Based on four harvests per year, 100 million crops could be grown on the vertical surfaces of Manchester worth between £200 million and £400 million per year based on a sale value between £2 and £4.

In total, between both vertical and horizontal surfaces, the city centre of Manchester is capable of growing an estimated 180.4 million

crops per year, achieving a maximum sale value of approximately £721.6 million per annum.

Framework of Integration

Light capture

Light capture is one of the key requirements for the successful integration of urban agriculture alongside access, demand and structural integrity. Manchester performs well in this respect with 99.4 percent of roof space and 45 percent of vertical surface providing suitable to excellent light capture. An aspect of the annual light study which has not been alluded to until this point, is the information it provides for the integration of urban agriculture. It would make little sense to roll out urban agriculture across all productive surfaces before first exploring and testing what systems are best suited to this scale of agriculture within the context of Manchester. Additional parameters to consider will also be how well a system performs against expected production, how the systems within the the city are run, who operates them, and where the produce is sold. The areas which receive the highest light levels would be the best sites for further analysis when testing the above. Beyond this, areas which receive less light can also be sought, in order to test a systems ability to perform in less than perfect conditions.

Prioritisation of implementation

The research collected to date on the operational elevated aquaponic system in Manchester, along side the facade farm prototype, shows that horizontal systems are easier to implement and to maintain. Although the ability of double skinned facades to grow crops is apparent, their integration is more dis-ruptive and far more complex. At the outset of integrating urban agricultural systems, the route of least resistance should first be taken in order to reduce expenditure, gain support and increase revenue streams. Therefore, roof space should be considered primarily as sites on which food can be grown with facade integration occurring at a later date. Initially, this might manifest itself as a succession of simple greenhouses or polytunnels upon roof tops (as per the polytunnel used in the elevated urban farm) to kick start urban food production, which future urban systems can build from and improve upon; most importantly flowing into newly created supply chains. The majority of north facing facades should only be considered for vertical systems in the event that all other growing opportunities have been explored.

Interface with food networks

The final factor considered within this study is the ability to sell food once it has been harvested from urban agricultural systems. Demand for the food grown is a key requirement for the successful integration of urban agriculture. Without demand for food there would be no sale of crops, and therefore no economic model. Growing food where it is needed - i.e. where it can be easily sold - will increase the ability of these technical food systems to sell crops closer to the rate of production, removing the possibility of surplus produce and ensuring a resilient economic model. The ability to sell food locally will also have the biggest impact on food transport, as changing from food miles to food steps will drastically reduce the distance food travels. The adjacency of food production and food sale will allow the continuous trade of fresh-
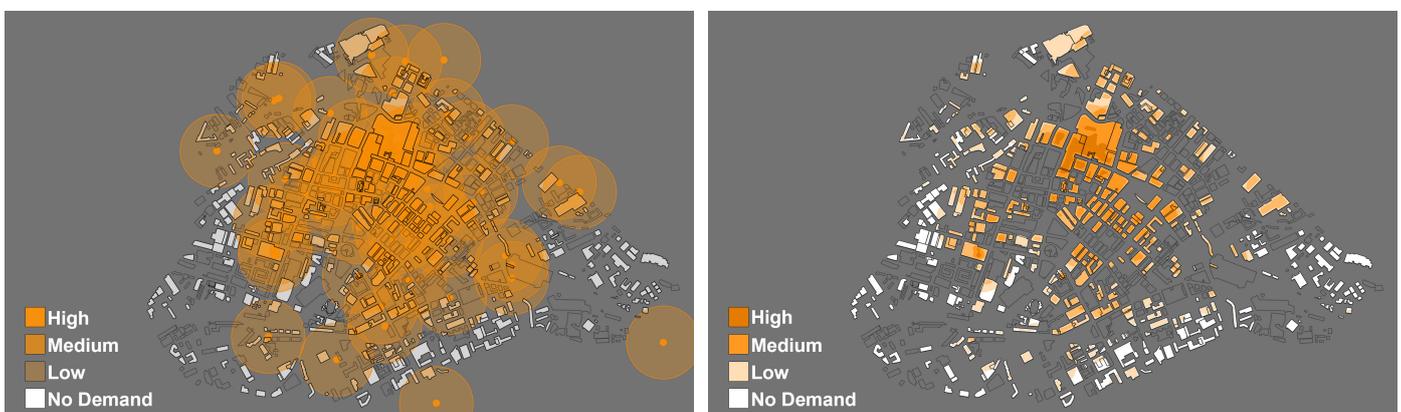

High
Medium
Low
No Demand

High
Medium
Low
No Demand

Figure 8: Location of 54 supermarkets including a 250m catchment area (left) and gradient map of demand (right)
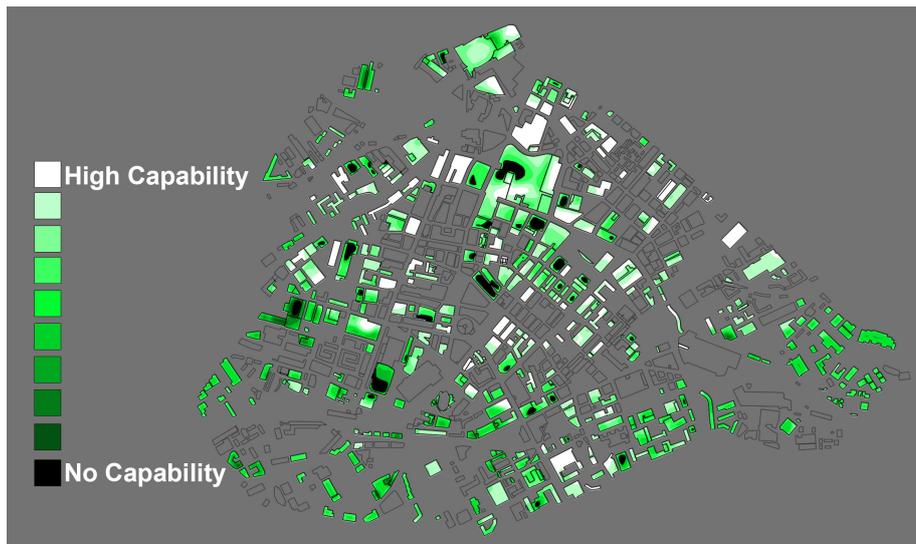
Figure 9: Roof top framework of integration based on light capture and demand.

ly harvested organic fruit and veg, with higher nutrient content, and little need for packaging or refrigeration. As a consequence, CO_2 production would decrease and urban diets would improve.

In total, there are 54 supermarkets in Manchester and, based on a 250m catchment area, the demand for available roof space would initially be 74 percent (Fig. 8). As a result of this, food would never travel further than 250m to its point of sale. The resulting gradient map based on these locations identifies the places that are in highest demand and where food might be initially grown (Fig. 8).

Framework of integration into the city
The framework of integration proposed within this research focuses on the availability of light and the findings discussed within the paper integrated with existing food networks and points of sale. (Fig. 9). This map is the culmination of the research as it identifies areas from most to least desirable for urban agricultural activities. This information shows both the areas of high light capture and high food demand in white, and the areas of low light capture and low food demand in dark green. The black areas are the areas identified previously as not being able to support plant life (i.e. having an average daily light capture throughout the year of less than 0.90 kW/m2/day) . The resulting information represents simply that the white areas be developed first, working through to the dark green areas as the role of food production within the city takes on a larger and more integrated role. This map is the resulting framework of integration and will

hopefully lead to a city no longer comprised solely of manmade surfaces, but a city integrated with a natural metabolism, intrinsic to its future prosperity.

Conclusions and Future Considerations

The findings of this paper show that cities are capable of producing large quantities of food and wealth but currently only includes for such crops as iceberg lettuce, rocket lettuce, Thai basil and cabbages - as per the crops grown in the elevated aquaponic system - but it is the future ambition of the research to develop the light study to include energy data of other crops and propose a city wide production map as to which crops are best suited to which light energy levels.

Taking the total surface area of Manchester into account - including roads, paths etc. - 33 percent is capable of growing food. Within the UK, 11 percent of the country has been developed. Applying the findings of Manchester, where the growing area was 1.5 times that of its footprint, it can be assumed for the purposes of this research, that 16.5 percent of the total land area of the UK could grow additional food.

As a model, urban agriculture is capable of producing vast amounts of food and wealth, but cannot solve the issues of globalised food production and transport alone. Instead, it sits amongst a range of options that need to be implemented in order to reduce the impact humans have on the natural landscape, and is a part of a series of interventions that include a reduction in meat
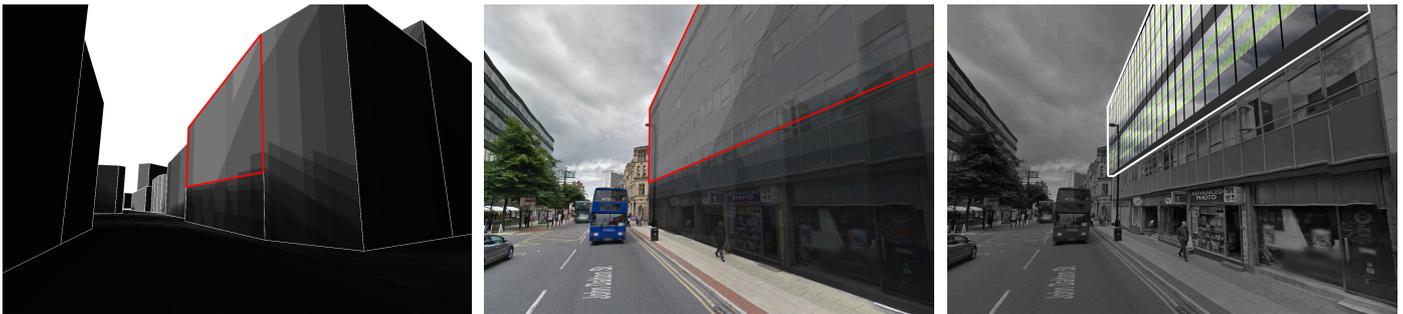
Figure 10: The use of three-dimensional shadow data to inform real-world urban food production

consumption, the adoption of clean renewable energy, the reduction of waste streams and the integration of closed loop urbanism, to name a few.

One thing is clear however, urban agriculture can be integrated within today's cities and produce vast quantities of food without the need for purpose built food producing sky scrapers that are dependent on artificial lighting to grow crops. Instead, the retrofitting of simplified food producing facades and roof-based systems based on virtual lighting data can make a real difference (Fig. 10). Urban agriculture is the start of a city revolution that connects the urban with the natural, improving the physical environments of cities forever and improving the wellbeing of its inhabitants for years to come.

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Conflict of Interests

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

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