SUPPLEMENTARY INFORMATION

The Potential of Urban Agriculture in Combination with Organic Waste Valorization: Integrated Assessment of Resource Flows and Operational Emissions for Two European Cities

Till Weidner*, Aidong Yang

University of Oxford, Parks Road, OX13JP, Oxford, United Kingdom

December, 2018

* Email: till.weidner@eng.ox.ac.uk

Contents

A. Spatial analysis . . . 4

A.1 Methodology . . . 4

A.2 List of data sources . . . 5

A.3 Minimum patch sizes for growing practices . . . 6

A.4 Ratios between growing practices . . . 7

A.5 Overview of considerations for non-productive growing area . . . 7

A.6 Removal of non-applicable ground space and narrow patches . . . 8

A.7 Accounting for greenhouse geometry . . . 10

A.8 Final area extract . . . 10

A.9 Roof type determination . . . 12

A.10 Crop allocation table . . . 12

B. Food production and current supply structure . . . 13

B.1 Table of yield values used . . . 13

B.2 Table of demand profile used (Western Europe) . . . 14

B.3 Table of import share . . . 15

B.4 Table of monthly import split . . . 16

B.5 Table of required PAR values for each crop . . . 16

B.6 Crop cycles . . . 17

B.7 Harvest tables for garden growing . . . 17

B.8 Hoop-house yield extension and storage . . . 18

B.9 Table of nutrient content of crops for hydroponics . . . 19

B.10 Fertilization rates for soil-based growing . . . 20

C. Climate curves and water requirements . . . 20

C.1 Rainfall data . . . 20

C.2 Temperature curves Glasgow . . . 21

C.3 Temperature curves Lyon . . . 21

C.4 Solar radiation curves Glasgow . . . 22

C.5 Solar radiation curves Lyon . . . 22

C.6 Irrigation and replenish water requirements . . . 23

D. Lighting and heating of greenhouses . . . 23

D.1 Overview of equations . . . 23

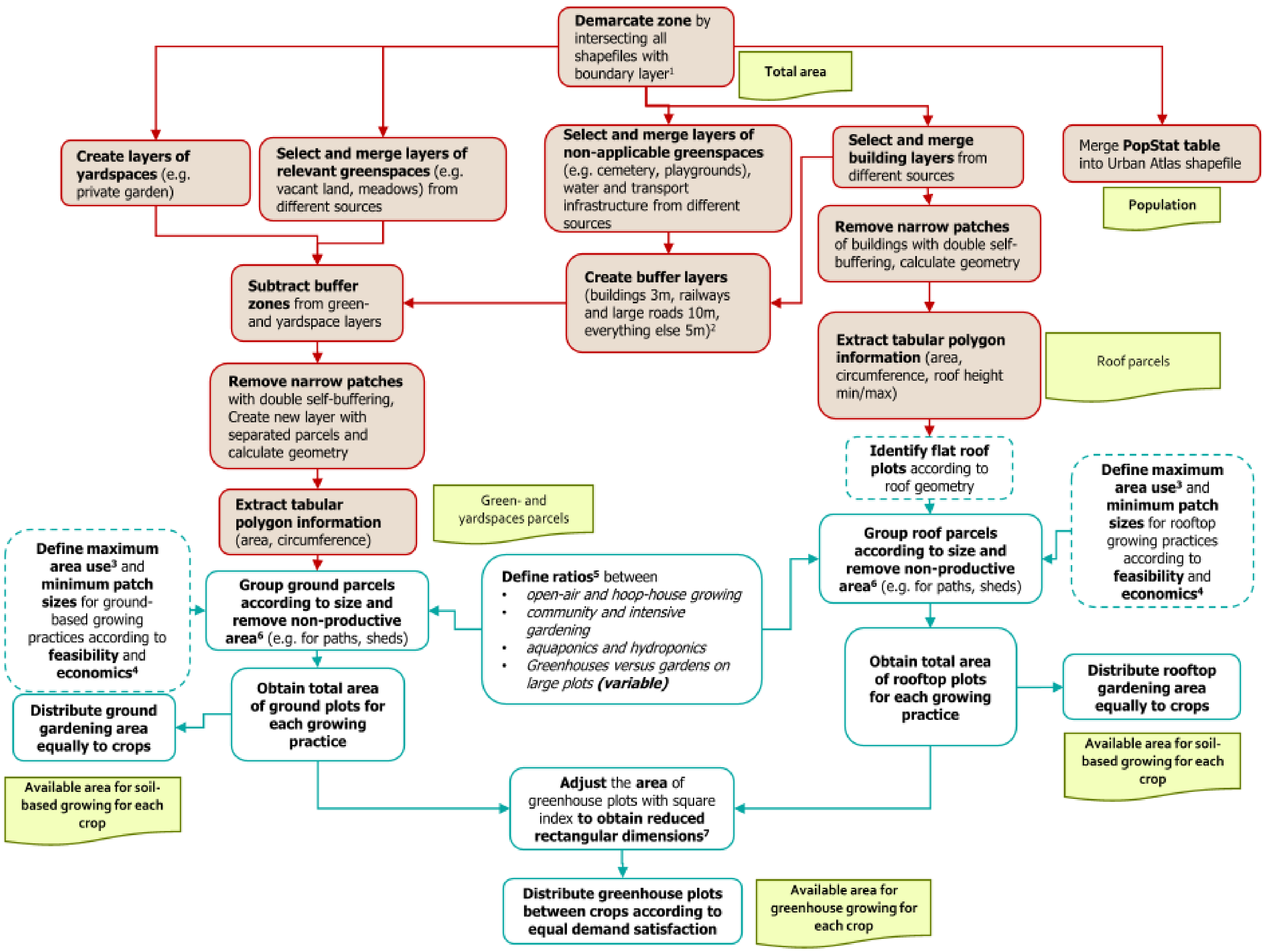
D.2 Overview of heating and lighting related parameter . . . 24

E. Process and waste parameter 25
E.1 Waste stream composition 25
E.2 Annual profiles - generation of yard waste and fertilization 25
E.3 Process considerations 25
E.4 Overview of process parameters 26
F. Emissions 28
F.1 Food emissions, domestic and import 28
F.2 Emissions of fish production and feed supply 29
F.3 Emission parameters 29
F.4 Formula for incineration 30
F.5 System boundary overview 30
G. Optimization 31
G.1 Superstructure 31
G.2 Mathematical formulation 32
G.3 Nomenclature 33
G.4 Mass flow without digestate constraint 34
H. Discussion of results 35
H.1 Spatial analysis 35
H.2 Distribution of growing area for 20/80 ratio 35
H.3 Comparison with other studies – Spatial analysis 35
H.4 Comparison with other studies – Resource requirements 36
H.5 Additional insights about difference between the two cities 37
References 39

A. Spatial analysis

A.1 Methodology

To assess available area, ArcGIS Pro 2.1 (https://pro.arcgis.com) was used for spatial analysis, for which information was extracted for further processing. This flow diagram shows the steps undertaken in ArcGIS Pro 2.1 (red boxed) and in Excel (white boxes). The green flags show the resulting output used in the calculation.



Description of footnotes: 1 see Goldstein et al. (2017), 2 see (Saha & Eckelman, 2017), 3 See Table 1 in main text, 4 see table A 3.5, 5 see table A.4, 6 see table A.5, 7 see Table A.7.

A range of data sources (A.2) was used for land use information as no single source alone was able to reflect reality appropriately. Building on previous studies and introducing several novel treatments, spatial data was stepwise refined:

- Each target city was zoned to obtain the correct population and appropriate area within the data layers (Goldstein, et al. 2017)
- Non-applicable areas (e.g. playgrounds, roads, cemeteries) including a buffer zone were deducted from selected greenspaces (e.g. parks, allotments, grass and vacant land)(Saha & Eckelman, 2017)
- Narrow stretches were removed in each plot (double buffering, A.6 in SI)
- Flat rooftops were identified by extracting geometric data, which were provided by the utilized building footprint layers (e.g. minimum and maximum roof height, A.9 in SI)
- To account for structural integrity and access logistics, the maximum available flat rooftop area was constrained (see table 1 and Nadal et al., (2017))
- To account for desirability and realistic expectations, the maximum area use of applicable ground based greenspaces was defined (see table 1 in main text)
- The resulting parcels were distributed between different growing practices (see figure 2 in main text). This was done by economic and practical considerations for minimum patch sizes (A.3 in SI) and sensible ratios between them (see table 1 in main text and A.4 in SI)
- The total area of greenhouse plots and rooftops was further reduced through adjusting the shape to account for non-rectangular geometry (A.7 in SI)
- Non-productive growing area was subtracted based on assumptions (e.g. for sheds, paths, A.5 in SI)
- For determining the final areas when varying ‘greenhouses versus gardens on large ground plots’, all steps in the white boxes with a continuous outline were repeated.

A.2 List of data sources

Aspect	Source	Online link and further details
Population (Lyon)	Urban Atlas Population Stat FR003L2_LYON_UA2012	https://land.copernicus.eu/local/urban-atlas
Population (Glasgow)	Urban Atlas PopStat UK004L1_GLASGOW_UA2012	https://land.copernicus.eu/local/urban-atlas
Greenspaces (Lyon and Glasgow)	OSM: allotments, park, grass, heath, meadow, scrub	http://download.geofabrik.de/europe/france/rhone-alpes-latest-free.shp.zip http://download.geofabrik.de/europe/great-britain/scotland-latest-free.shp.zip
	Urban Atlas 2012: Arable land, land without current use, green urban areas, herbaceous vegetations associations, open spaces with little or no vegetation,	https://land.copernicus.eu/local/urban-atlas FR003L2, UK004L1
Yardspaces (Lyon)	Urban Atlas 2012: urban fabric >30% density (=yard spaces)	https://land.copernicus.eu/local/urban-atlas FR003L2
Green- and yard spaces (Glasgow)	Greenspaces: Allotments or community growing space, institutional grounds, natural, land use changing, public park or garden, amenity- transport, school grounds, amenity – residential or business Yardspaces: private gardens	OS MasterMap® Topography Layer [FileGeoDatabase geospatial data], Scale 1:1250, Tiles: GB, Updated: 1 November 2017, Ordnance Survey (GB), Using: EDINA Digimap Ordnance Survey Service, <http://digimap.edina.ac.uk>, Downloaded: 2018-06-21 19:10:41.21
Buildings and roof	Volumes de toiture 3D du bati de la Métropole de Lyon	https://data.grandlyon.com

height (Lyon)		
Buildings and roof height (Glasgow)	OS MasterMap® Building Heights	OS MasterMap® Building Heights [FileGeoDatabase geospatial data], Scale 1:2500, Tiles: ns55nw, ns56sw, ns56nw, ns57sw, ns55ne, ns56se, ns56ne, ns57se, ns65nw, ns66sw, ns66nw, ns67sw, ns65ne, ns66se, ns66ne, ns67se, ns75nw, ns76sw, ns76nw, ns77sw Updated: 23 October 2017, Ordnance Survey (GB), Using: EDINA Digimap Ordnance Survey Service, <http://digimap.edina.ac.uk>, Downloaded: 2018-06-21 13:48:39.96
Boundary zone (Lyon)	Circonscriptions métropolitaines 2018 de la Métropole de Lyon: Circonscriptions 2,8,9,11	https://data.grandlyon.com
Boundary zone (Glasgow)	GLASGOW_PER as selection of scotland_and_wales_const.shp in Digimap Boundaryline	https://digimap.edina.ac.uk/webhelp/resources/index.html
Non-applicable ground space (Lyon and Glasgow)	OpenStreetMap: water, waterways, transport, traffic, roads, land use (cemetery, recreation_ground, forest, orchard), POIS (graveyard, pitch, playground, swimming_pool, sports_centre, stadium, goldcourse, farm	http://download.geofabrik.de/europe/france/rhone-alpes-latest-free.shp.zip http://download.geofabrik.de/europe/great-britain/scotland-latest-free.shp.zip
	Urban Atlas: Forests, Sports and leisure facilities	https://land.copernicus.eu/local/urban-atlas UK004L1_GLASGOW_UA2012 FR003L2_LYON_UA2012
Non-applicable ground space (Glasgow)	OS MasterMap Greenspace: cemetery, gold course, other sports facility, play space, playing field, tennis court, religious grounds	OS MasterMap Greenspace [SHAPE geospatial data], Scale 1:2500, Tiles: ns55nw, ns56sw, ns56nw, ns57sw, ns55ne, ns56se, ns56ne, ns57se, ns65nw, ns66sw, ns66nw, ns67sw, ns65ne, ns66se, ns66ne, ns67se, ns75nw, ns76sw, ns76nw, ns77sw, Updated: 29 March 2018, Ordnance Survey (GB), Using: EDINA Digimap Ordnance Survey Service, <http://digimap.edina.ac.uk>, Downloaded: 2018-06-21 13:48:39.972

A.3 Minimum patch sizes for growing practices

Only plots or parcels above this threshold would be considered applicable for the type of growing practice.

Growing practice	**Minimum area**	**Justification**
Community garden (open-air)	25 m^2	Min. practical limit
Community garden (hoop-houses)	75 m^2	Min. practical limit
Professional garden (ground based)	250 m^2	Min. economic and practical limit
Integrated AD or aquaponics greenhouse (ground based)	750 m^2	Min. economic limit
Professional garden (rooftop)	100 m^2	Min. practical limit (e.g. produce

		logistics within buildings)
Rooftop greenhouse – high-value crops (lettuce and strawberry)	500 m^2	Min. economic limit (Nadal, Alamús, et al., 2017)
Rooftop greenhouse – medium-value crops	1000 m^2	Min. economic limit (Fesquet, 2015)
Rooftop greenhouse - Aquaponics	2500 m^2	Min. economic limit

A.4 Ratios between growing practices

Due to the classification below, larger plots and parcels would be applicable to a range of growing practices. The ratios in the following table defined the actual use of parcels of a certain size and distributed the available areas accordingly. This was done only considering the total area and dividing it up, rather than allocating a specific parcel with a specific size based on the probability.

Growing practices	Ratio	Justification
Open-air vs hoop-houses (both ground based and on rooftop gardens)	50/50	Equal share, hoop-houses extend season but open-air gardens with more urban ecosystem services
Professional vs community garden (both ground based and on rooftop gardens)	50/50	Equal share, focus either on productivity or social benefits
Gardens vs greenhouses on large ground plots (ground based only)	Variable	Besides a higher footprint, public acceptance of greenhouses (e.g. aesthetic reasons) is likely limited
Aquaponics vs integrated AD greenhouses (ground based only)	50/50	Equal share, both functions desired (fish production and waste conversion)
Gardens vs greenhouses on large rooftops	25/75	Assumption that on 25% of applicable flat roofs greenhouses are not allowed (e.g. fire safety) or desired
Aquaponics vs Hydroponics greenhouses (rooftops)	25/75	Assumption that only 25% of applicable flat roofs have required structural integrity

A.5 Overview of considerations for non-productive growing area

In gardens on greenhouses, space was considered to allow for to growing beds, tool storage and other non-productive area uses.

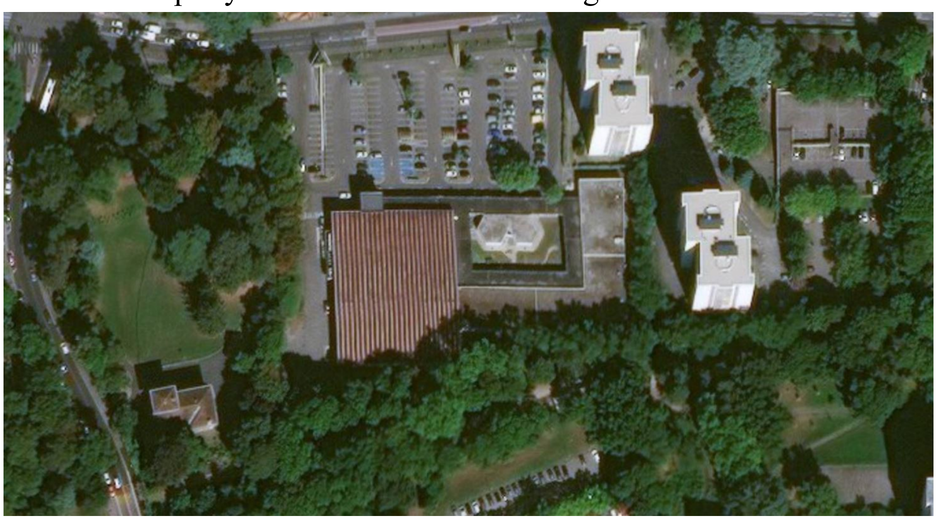
Growing practice	Productive growing area	Justification
Community garden (open-air)	80%	Paths, sheds, meeting spaces
Intensive garden (open-air)	85%	Paths, sheds
Hoop-house (interior area in relation to built area)	90%	Round roof restricts usable area
Hoop-house (inside)	80%	Paths, equipment
Ground-based greenhouse (interior area in relation to built area)	95%	Structure and foundation restricts internal area
Ground-based greenhouse (inside)	70%	Both aquaponics (e.g. tanks) and integrated greenhouses (e.g.

		digestion chamber) need space for equipment
Rooftop gardens (built area in relation to flat roof area)	95%	Safety distance between end of roof and plots
Rooftop gardens	85%	Paths, equipment
Rooftop greenhouse (built area in relation to flat roof area)	100%	Rooftop structure is extension to wall
Rooftop greenhouse (inside)	75%	Increased space requirements for pumps and other equipment

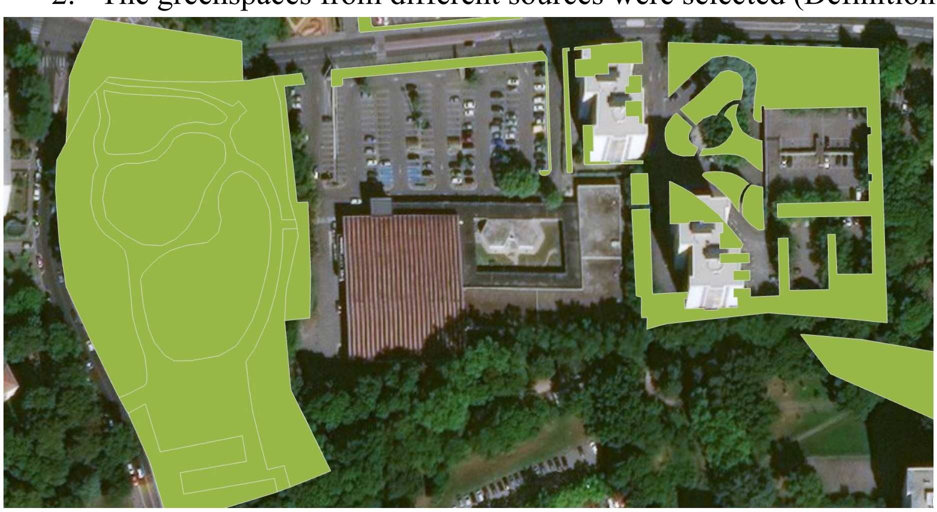
A.6 Removal of non-applicable ground space and narrow patches

A range of data sources was used which defined greenspaces or other applicable land differently, in addition some sources would have multiple definitions for specific area, e.g. a playground in a park would have the land use properties of "playground" as well as "public greenspace". Therefore, all areas were removed for which conversion to gardens would be undesired (e.g. soccer field) or not sensible (e.g. conversion of forest). Furthermore, spatial analysis employs satellite or other remotely sensed data sources with increasingly high resolution, meaning that identified parcels for a certain land use might be quite small or have very narrow patches. To take into account both considerations, the following sequence was employed as geoprocessing steps in ArcGIS Pro.

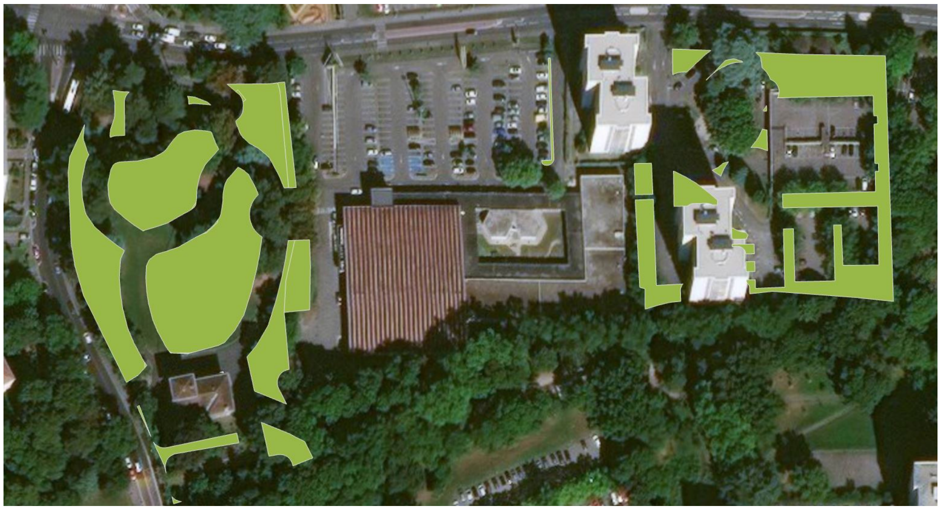
1. Exemplary screenshots – satellite image



2. The greenspaces from different sources were selected (Definition Query) merged together



3. Non-applicable ground spaces were selected, merged and erased from the greenspace layer



4. Narrow patches were removed by double-buffering (pictures shows -+5 m buffering)

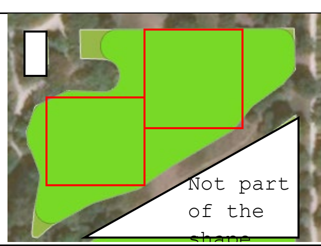
The same method to remove narrow patches was applied for building rooftops (the grey is the initial footprint and the red the modified one. Some roofs have different heights and thus a range of narrow patches with the same height

5. The polygons were separated (multipart to singlepart) and the geometry was calculated and in table form extracted. Given the minimum limits on parcel size, the 3 smaller polygons in the upper picture were excluded.

A.7 Accounting for greenhouse geometry

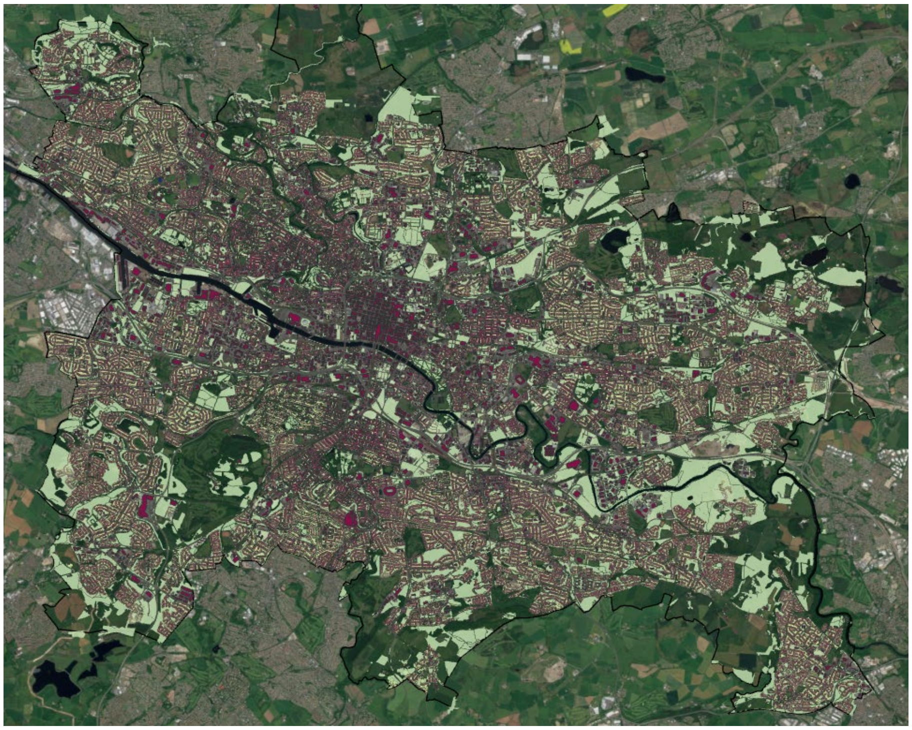
As can be seen in the pictures above, many areas do not have rectangular shapes, hence a greenhouse built on one of them would have a much reduced ground surface area.
By manually measuring some shapes and determining a realistic greenhouse footprint (using rectangles), it was found that the square index, defined as $\frac{16*A}{P^2}$, which indicates how similar the shape is to a square, can be used to automatically process all shapes at once to satisfying accuracy. One can see that the square index of s shape is 1 if it is a square, >1 if it is more round and <1 if it is more polygonal (i.e. many edges and corners, potentially with holes and gaps).

The following figure illustrates this by using a few sample polygons. With the measure tool in ArcGIS Pro, the realistic area for a greenhouse was measured in two ways, the minimum fitting rectangle (see shape 1 below) area and a "stretch" area (see shape 2 below), implying a greenhouse that is not fully rectangular (e.g. L shape) but also does not have any round edges or infeasible shapes. It can be seen that the square index is always in between the measured values, hence does neither under- or overestimate the area. This test was repeated for several shapes with diverse geometry. The calculation steps included the square index, a check whether it is <1 or >1 and the subsequent multiplication (if <1) or division (if >1) of the area value.

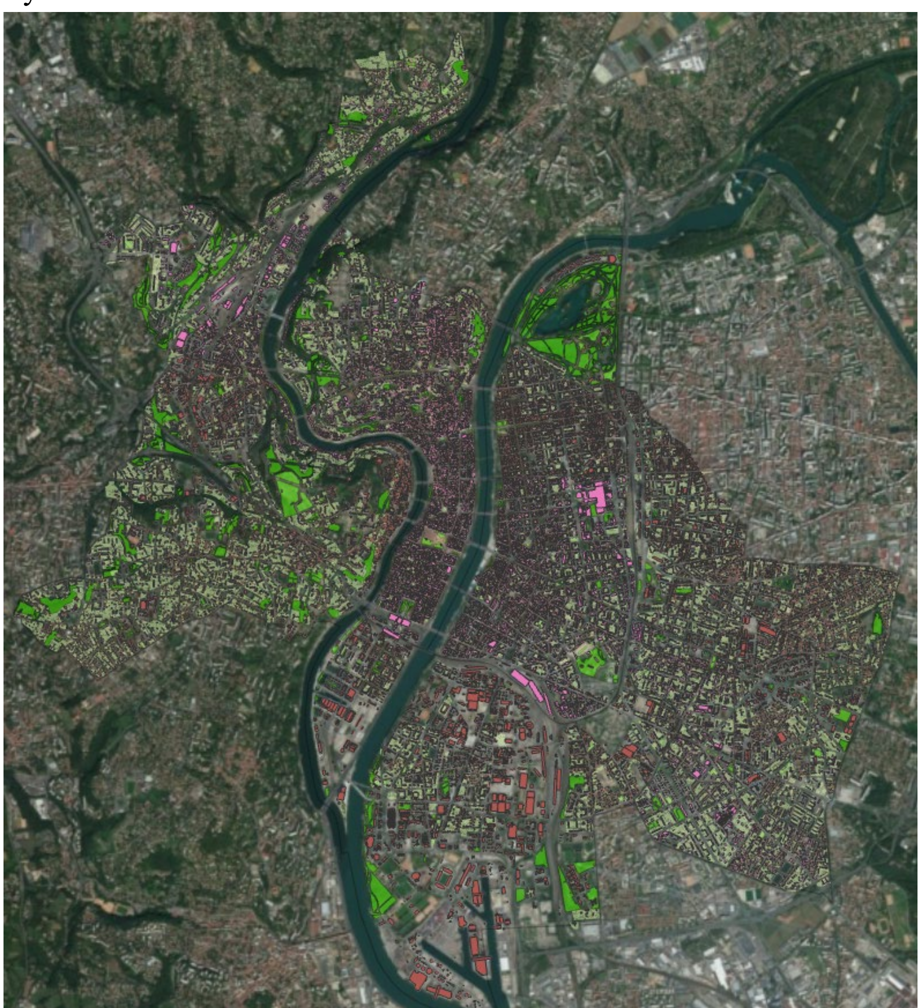
Aspect	Shape 1	Shape 2	Shape 3
Area (m^2)	2848.832573	1978.831987	1517.266116
Perimeter (m)	244.303159	195.223983	171.527442
Rectangles (m^2)	1720	1097	965.92
Corresponding multiplicator	0.60375608	0.55436743	0.63661871
Stretch rectangle (m^2)	2394	1696	1370
Corresponding multiplicator	0.84034422	0.85707125	0.90293982
Index squarity	0.76370868	0.83073317	0.82511314
Screenshot of shape			

A.8 Final area extract

Glasgow



Lyon



A.9 Roof type determination

The building datasets from Lyon and Glasgow included roof height information obtained from remote sensing. The two values used were the total roof height and the height of the façade or wall. Since over 50,000 building polygons were extracted in table format, automatic processing was imperative. Since only the roof height, the area and the perimeter was available, it was assumed that houses are round and roofs are conical. Using the roof height and the radius, the slope was determined and only buildings with a roof slope below 5 degrees were considered. As shown in the table below, the area was adapted according to the square index and the resulting area allocated to the category depending on their cut-off points (in this case open-air >100m^2, high-value crop RTGs >500m^2, medium-value crop RTGs >1000m^2 and AP > 2500m^2). It has to be noted that this categorization was only the first step and the actual areas available for each growing practices was determined by the ratios between them as described above (if more than 1 practice was applicable for a certain size).

1	htotale	hfacade	ape_Leng	hape_Are	Height roof	height / radius	Slope <max	Squarity index	Factor	Final area	Open-air	HV RTG	MV RTG	AP / RTG
17842	4.1	4.1	50.23921	167.3539	0	0	1	1.061	0.943	157.749	157.748622			
17843	24.3	24.3	79.01385	220.7372	0	0	1	0.566	0.566	124.872	124.871881			
17844	5.2	5.2	29.65152	56.09206	0	0	1	1.021	0.980	54.951				
17845	21.4	18.6	125.9108	570.9805	2.8	0.207693233	0	0.576	0.576	329.031				
17846	26.4	26.4	107.5431	513.5295	0	0	1	0.710	0.710	364.826	364.82576			
17847	26.5	26.5	87.68002	402.7563	0	0	1	0.838	0.838	337.601	337.600795			
17848	2.7	2.7	26.04085	49.01204	0	0	1	1.156	0.865	42.383				
17849	18.3	18.3	61.37428	218.6808	0	0	1	0.929	0.929	203.127	203.127409			
17850	23.5	21	110.4947	610.3641	2.5	0.179357873	0	0.800	0.800	488.219				
17851	13.9	11.3	444.9418	10110	2.6	0.045832417	1	0.817	0.817	8260.676				8260.67648
17852	19.5	13.9	44.83663	155.6418	5.6	0.795609186	0	1.239	0.807	125.645				
17853	22.3	18.3	199.5608	1423.82	4	0.187891637	0	0.572	0.572	814.479				
17854	18.1	14.5	75.92004	269.2431	3.6	0.388870644	0	0.747	0.747	201.232				
17855	6.8	4.1	38.58122	105.6947	2.7	0.465491897	0	1.136	0.880	93.032				
17856	2.8	1	28.83482	52.16783	1.8	0.441718958	0	1.004	0.996	51.965				
17857	17.7	17.7	52.47303	189.1116	0	0	1	1.099	0.910	172.089	172.08866			
17858	15.1	15.1	64.2054	151.7089	0	0	1	0.589	0.589	89.330				
17859	17.9	17.9	46.55651	120.8963	0	0	1	0.892	0.892	107.891	107.890924			
17860	11.7	11.7	29.5448	60.46247	0	0	1	1.108	0.902	54.556				
17861	14.4	14.4	35.2458	76.36736	0	0	1	0.984	0.984	75.114				
17862	17	17	47.6908	99.32245	0	0	1	0.699	0.699	69.398				
17863	17.1	17.1	59.18599	135.6845	0	0	1	0.620	0.620	84.090				
17864	15.2	15.2	152.2782	520.4697	0	0	1	0.359	0.359	186.911	186.911388			
17865	19.2	19.2	32.43354	71.31452	0	0	1	1.085	0.922	65.746				
17866	2.5	2.5	30.84632	59.52175	0	0	1	1.001	0.999	59.468				
17867	46	46	37.42353	77.01553	0	0	1	0.880	0.880	67.762				
17868	46	46	38.11802	79.5899	0	0	1	0.876	0.876	69.755				
17869	10.5	10.5	69.2367	286.4648	0	0	1	0.956	0.956	273.899	273.898564			
17870	24.2	18.5	72.25908	332.391	5.7	0.554147207	0	1.019	0.982	326.336				
17871	8.5	8.5	53.71568	193.4421	0	0	1	1.073	0.932	180.336	180.335915			
17872	13.1	13.1	130.9058	1004.621	0	0	1	0.938	0.938	942.339		942.3388		
17873	13.8	13.8	71.79267	329.9525	0	0	1	1.024	0.976	322.137	322.13669			
17874	18.1	18.1	40.55008	98.49241	0	0	1	0.958	0.958	94.394				
17875	18.1	18.1	39.85003	88.02213	0	0	1	0.887	0.887	78.063				
17876	18.1	18.1	38.38278	96.7998	0	0	1	1.051	0.951	92.077				
17877	8.6	8.6	24.96812	40.71514	0	0	1	1.045	0.957	38.963				
17878	22	22	70.70948	224.1863	0	0	1	0.717	0.717	160.836	160.835852			
17879	6.2	6.2	78.23072	342.2212	0	0	1	0.895	0.895	306.182	306.18166			
17880	21.9	21.9	83.80859	378.8455	0	0	1	0.863	0.863	326.939	326.93929			
17881	8.8	8.8	45.10318	115.255	0	0	1	0.906	0.906	104.478	104.478011			
17882	8.8	8.8	44.90922	123.8839	0	0	1	0.983	0.983	121.753	121.752757			
17883	4.6	2.1	35.91773	84.45411	2.5	0.482174832	0	1.047	0.955	80.630				
17884	9	7.2	37.48829	96.87052	1.8	0.324154179	0	1.103	0.907	87.836				
17885	4.5	1	48.66883	144.1154	3.5	0.51675871	0	0.973	0.973	140.294				
17886	10.9	8.4	42.81077	130.2156	2.5	0.388314416	0	1.137	0.880	114.548				
17887	13.2	11.4	40.78664	118.3132	1.8	0.293312675	0	1.138	0.879	103.972				
17888	4.4	3.5	31.89563	71.28689	0.9	0.188935091	0	1.121	0.892	63.583				
17889	22	18.4	58.56419	235.8812	3.6	0.415461515	0	1.100	0.909	214.360				
17890	17.4	15.2	30.52198	61.84468	2.2	0.495845582	0	1.062	0.941	58.224				
17891	16.1	13.5	52.949	192.6211	2.6	0.332044578	0	1.099	0.910	175.225				
17892	5.9	3.7	28.7489	47.99481	2.2	0.562860117	0	0.929	0.929	44.593				
17893	11	9.7	31.8837	69.84196	1.3	0.275714791	0	1.099	0.910	63.536				
17894	7.3	3.9	37.30181	98.86685	3.4	0.606077983	0	1.137	0.880	86.964				
17895	8.6	7.4	73.45175	274.3299	1.2	0.128416139	0	0.814	0.814	223.183				

A.10 Crop allocation table

For soil-based gardens and garden hoop-houses, crops were allocated between the growing practices based on equal ratios. For high-intensive greenhouse growing, crops were allocated based on equal contribution to demand satisfaction. The latter was determined by setting one growing practice as the only active one (i.e. all greenhouse-applicable plots would only incorporate that practice) and using Solver® in Excel to determine the area split between the crops grown in this practice by minimizing the deviation from the average demand satisfaction of those crops. An example for high-value RTGs is given in the formula below using the self-sufficiency (S) of strawberries (sb) and lettuce (lc)

$$Minimise\{(Average(S^{sb}, S^{lc}) - S^{sb})^2 + (Average(S^{sb}, S^{lc}) - S^{sb})^2\}$$

where S^{sb} and S^{lc} are a function of the area split between them.
The ratio between lettuce and strawberries area allocation was found so that the demand satisfaction, i.e. the self-sufficiency percentage, would be equal for both crops)

Type	Crop	Open-air gardens	Hoop-houses in gardens	Aquaponics or integrated AD greenhouses	High-value rooftop greenhouses	Medium-value rooftop greenhouses
Fruits	Blueberries	0.091				
	Cantaloupe		0.111			
	Grapes	0.091				
	Raspberries	0.091				
	Strawberries	0.091		0.088	0.301	
	Watermelon		0.111	0.085		0.108
Vegetable	Green beans		0.111			
	Broccoli and Cauliflower	0.091				
	Cabbage		0.111	0.232		0.295
	Carrots		0.111			
	Cucumber	0.091		0.082		0.104
	Leeks	0.091				
	Lettuce		0.111	0.123	0.699	
	Onions	0.091				
	Peas	0.091				
	Peppers (bell)		0.111	0.138		0.175
	Squash		0.111			
	Spinach		0.111			
	Tomato	0.091		0.221		0.280
	Turnip	0.091		0.031		0.039

B. Food production and current supply structure

B.1 Table of yield values used

Type	**Crop**	**Soil-based growing UK (kg/m²)**	**Soil-based growing France (kg/m²)**	**Hydroponic yields (kg/m²)**	**Sources**
Fruits	Blueberries	0.339	0.392		FAOSTAT production yield average 2014-16, UK from Denmark
	Cantaloupe	2.874	1.847		FAOSTAT production yield average 2014-16, UK from Netherlands
	Grapes	0.118	0.825		FAOSTAT production yield average 2014-16 production yield
	Raspberries	1.099	0.630		FAOSTAT production yield average 2014-16

	Strawberries	2.440	1.756	24.1	FAOSTAT production yield average 2014-16, (Shao et al., 2016)
	Watermelon	1.104	1.930	34.7	FAOSTAT production yield average 2014-16, (Shao et al., 2016)
Vegetable	Green beans	1.005	0.662		FAOSTAT production yield average 2014-16, UK from Russia
	Broccoli and Cauliflower	0.970	1.599		FAOSTAT production yield average 2014-16
	Cabbage	2.827	2.662	26.922	FAOSTAT production yield average 2014-16, HP: (Haberman et al., 2014)
	Carrots	6.613	4.564		FAOSTAT production yield average 2014-16
	Cucumber	1.860	1.860	63.03	Soil-based and HP from Haberman et al. (2014) as FAOSTAT figure is mostly for greenhouse production
	Leeks	2.143	3.146		FAOSTAT production yield average 2014-16
	Lettuce	2.148	2.628	43.025	FAOSTAT production yield average 2014-16, HP: (Haberman et al., 2014)
	Onions	4.136	3.537		FAOSTAT production yield average 2014-16
	Peas	0.445	0.711		FAOSTAT production yield average 2014-16
	Peppers (bell)	2.568	3.988	23.33	FAOSTAT production yield average 2014-16, HP: (Haberman et al., 2014)
	Squash	1.407	2.472		FAOSTAT production yield average 2014-16, UK from Denmark
	Spinach	0.965	2.003		FAOSTAT production yield average 2014-16, UK from Denmark
	Tomato	1.334	1.334	42.86	Soil-based and HP from Haberman et al. (2014) as FAOSTAT figure is mostly for greenhouse production
	Turnip	6.613	4.564	87.6	FAOSTAT production yield average 2014-16, HP: (Haberman et al., 2014)

B.2 Table of demand profile used (Western Europe)

Type	Crop	Percentage	Source
Fruits (100%)	Blueberries	1.404	FAOSTAT (import+production-export) in 2016
	Cantaloupe	18.809	FAOSTAT (import+production-export) in 2016
	Grapes	45.994	FAOSTAT food supply quantity 2016
	Raspberries	0.493	FAOSTAT (import+production-export) in 2016
	Strawberries	13.913	FAOSTAT (import+production-export) in 2016
	Watermelon	19.386	FAOSTAT (import+production-export) in 2016
Vegetable (100%)	Green beans	2.138	FAOSTAT (import+production-export) in 2016
	Broccoli and Cauliflower	4.925	FAOSTAT (import+production-export) in 2016
	Cabbage	10.265	FAOSTAT (import+production-export) in 2016
	Carrots	13.408	FAOSTAT (import+production-export) in 2016
	Cucumber	8.441	FAOSTAT (import+production-export) in 2016
	Leeks	2.948	FAOSTAT (import+production-export) in 2016
	Lettuce	8.716	FAOSTAT (import+production-export) in 2016
	Onions	14.057	FAOSTAT (import+production-export) in 2016
	Peas	3.067	FAOSTAT (import+production-export) in 2016

	Peppers (bell)	5.271	FAOSTAT (import+production-export) in 2016
	Squash	4.110	FAOSTAT (import+production-export) in 2016
	Spinach	2.673	FAOSTAT (import+production-export) in 2016
	Tomato	15.511	FAOSTAT (import+production-export) in 2016
	Turnip	4.469	FAOSTAT (import+production-export) in 2016

The absolute amounts were determined by multiplying the percentage with 83.3 g/person/day for fruits and 333.3 g/person/day for vegetables and then multiplying that with the population figure for each city.

B.3 Table of import share

Type	Crop	UK - Total share of import (%)	France - Total share of import (%)	Sources
Fruits	Blueberries	93.3	47.5	FAOSTAT (import quantity / supply quantity) 2016
	Cantaloupe	99.3	45.3	FAOSTAT (import quantity / supply quantity) 2016
	Grapes	100.0	0.0	FAOSTAT (import quantity / supply quantity) 2016
	Raspberries	0.0	0.0	FAOSTAT (import quantity / supply quantity) 2016
	Strawberries	32.5	62.9	FAOSTAT (import quantity / supply quantity) 2016
	Watermelon	95.6	100.0	FAOSTAT (import quantity / supply quantity) 2016
Vegetable	Green beans	85.2	63.4	FAOSTAT (import quantity / supply quantity) 2016
	Broccoli and Cauliflower	48.2	20.9	FAOSTAT (import quantity / supply quantity) 2016
	Cabbage	16.6	22.6	FAOSTAT (import quantity / supply quantity) 2016
	Carrots	7.2	24.7	FAOSTAT (import quantity / supply quantity) 2016
	Cucumber	75.1	39.2	FAOSTAT (import quantity / supply quantity) 2016
	Leeks	28.4	14.6	FAOSTAT (import quantity / supply quantity) 2016
	Lettuce	66.7	42.8	FAOSTAT (import quantity / supply quantity) 2016
	Onions	16.3	14.0	FAOSTAT (import quantity / supply quantity) 2016
	Peas	8.7	0.0	FAOSTAT (import quantity / supply quantity) 2016
	Peppers (bell)	91.7	99.1	FAOSTAT (import quantity / supply quantity) 2016
	Squash	98.8	72.3	FAOSTAT (import quantity / supply quantity) 2016
	Spinach	96.9	0.0	FAOSTAT (import quantity / supply quantity) 2016
	Tomato	80.4	57.7	FAOSTAT (import quantity / supply quantity) 2016
	Turnip	7.2	24.7	FAOSTAT (import quantity / supply quantity) 2016

B.4 Table of monthly import split

To increase the accuracy and reflect the seasonal variation in the current supply chain, the share of import as shown above was used to create an assumed supply ratio for every month which matched the annual supply ratio.

January	February	March	April	May	June	July	August	Septembe	October	Novembe	December
100	100	100	100	90	75	75	85	90	100	100	100
100	100	100	100	100	98	98	98	98	100	100	100
100	100	100	100	100	100	100	100	100	100	100	100
0	0	0	0	0	0	0	0	0	0	0	0
60	100	60	30	30	0	0	0	0	0	0	30
100	100	100	100	100	90	90	85	90	95	100	100
100	100	100	100	100	100	75	60	50	60	75	100
100	100	100	100	100	50	0	0	0	0	0	30
25	0	25	50	50	25	0	0	0	0	0	25
5	40	45	0	0	0	0	0	0	0	0	0
95	95	95	95	95	55	50	40	40	55	90	95
100	100	100	25	0	0	0	0	0	0	0	0
100	100	100	75	50	50	50	50	50	50	50	75
0	0	25	50	75	50	0	0	0	0	0	0
0	0	25	25	50	0	0	0	0	0	0	0
100	100	100	100	100	90	80	80	80	80	90	100
100	100	100	100	98	98	98	98	98	98	100	100
100	100	100	95	95	95	95	95	95	95	100	100
95	95	95	95	95	95	75	50	45	50	75	95
10	25	50	0	0	0	0	0	0	0	0	0

Glasgow

January	February	March	April	May	June	July	August	Septembe	October	Novembe	December
100	100	100	100	70	0	0	0	0	0	0	100
100	100	100	100	50	0	0	0	0	0	0	100
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
100	100	100	90	70	35		25	25	25	35	90
100	100	100	100	100	100	100	100	100	100	100	100
100	100	100	100	80	70	30	30	10	20	50	70
80	90	50	30	0	0	0	0	0	0	0	0
35	0	35	60	70	35	0	0	0	0	0	35
5	40	45	0	0	0	0	0	0	0	0	0
60	100	100	100	80	0	0	0	0	0	0	30
0	75	100	0	0	0	0	0	0	0	0	0
60	80	90	50	30	30	30	10	30	30	30	40
0	0	15	40	65	50	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
100	100	100	100	100	100	97	97	97	97	97	100
100	100	100	100	70	60	50	30	50	60	70	90
0	0	0	0	0	0	0	0	0	0	0	0
80	80	80	80	80	75	40	10	5	10	75	80
70	80	100	50	0	0	0	0	0	0	0	0

Lyon

B.5 Table of required PAR values for each crop

Type	**Crop**	**PAR (mol / m^2 / day)**	**Source**
Fruit	Strawberries	11.1	(Shao et al., 2016)
	Watermelon	15.1	(Shao et al., 2016)
Vegetable	Cabbage	17.0	(Shao et al., 2016)
	Cucumber	16.2	(Shao et al., 2016)
	Lettuce	17.0	(Shao et al., 2016)
	Peppers (bell)	10.8	(Shao et al., 2016)
	Tomato	13.5	(Shao et al., 2016)
	Turnip	14.4	(Shao et al., 2016)

The required PAR was either fully supplied by the natural sunlight or through artificial lighting when natural sunlight fell below those values (described in main text section 2.3)

B.6 Crop cycles

Type	Crop	Crop cycle in days (rounded value used for irrigation)	Sources
Fruits	Blueberries	(90)	Assumption / no season extension
	Cantaloupe	101 (90)	(Orsini et al., 2014)
	Grapes	(90)	Assumption / no season extension
	Raspberries	(90)	Assumption / no season extension
	Strawberries	(90)	Assumption / no season extension
	Watermelon	82 (90)	(Orsini et al., 2014)
Vegetable	Green beans	48-60 (60)	(KZNDARD, n.d.) https://www.growveg.co.uk/guides/quick-maturing-plants-5-fast-growing-vegetables-to-try/
	Broccoli and Cauliflower	(60)	Assumption / no season extension
	Cabbage	65-120 (90)	(KZNDARD, n.d.),
	Carrots	80-120 (90) 60 [baby carrots]	(KZNDARD, n.d.) https://www.growveg.co.uk/guides/quick-maturing-plants-5-fast-growing-vegetables-to-try/
	Cucumber	60-70 (60) 50 [baby cucumber]	(KZNDARD, n.d.) http://www.naturallivingideas.com/18-fastest-growing-veggies-can-harvest-no-time/
	Leeks	150 (150)	(KZNDARD, n.d.)
	Lettuce	44-62 (60)	(Orsini et al., 2014)
	Onions	140-180 (150)	(KZNDARD, n.d.)
	Peas	60-80 (60)	(KZNDARD, n.d.)
	Peppers (bell)	60-80 (60)	(KZNDARD, n.d.), https://harvesttotable.com/vegetable_harvest_times/
	Squash	85-110 (90) 40 [mini squash]	(KZNDARD, n.d.), https://www.hgtv.com/outdoors/gardens/garden-styles-and-types/vegetables-you-can-grow-in-two-months-or-less-pictures
	Spinach	40-55 (45) 30	(KZNDARD, n.d.), https://www.growveg.co.uk/guides/quick-maturing-plants-5-fast-growing-vegetables-to-try/
	Tomato	95-99 (90)	(Orsini et al., 2014)
	Turnip	55-60 (60)	www.wikipedia.org

The crop cycles were used in conjunction with the harvest tables (B.7) to determine the potential yield extension in hoop-houses (B.8) and to determine when a certain growing area requires irrigation (the values in brackets were the days before the first harvest date when irrigation had to start).

B.7 Harvest tables for garden growing

The table was created based on the harvest table used by Colasanti & Hamm (2010) for Michigan, considering both open-air growing and hoop-house growing on ground based and rooftop gardens. The tables also included for how long a crop could be stored (cold storage but without refrigeration), which was applied for 5 crops as shown in B.8. Despite the differing geographic location, the seasonal preference and dynamics of crops does not change significantly and the temperature and solar radiation profiles are comparable to Lyon. The differences in yields are already reflected in the nationally reported data, hence the harvest table was merely the orientation for when a crop is usually harvested. Furthermore, the slightly favourable growing climate in hoop-houses would cause a comparable growing season extension as in Michigan. The annual yields (from B.1) were divided by the harvest period (number in months) distributed over the months in which harvest (including storage) could be expected, e.g. if harvest is possible from mid-May to late July, then the mass of the annual yield would be distributed in the ratio 0.2 : 0.4 : 0.4 for May, June and July respectively.

Harvest map (open-air)													
1= field fresh													
2 = hoop-house	January	February	march	April	May	June	July	August	Septemb	October	Novembe	December	
	1	1	1	1	1	1	1	1	1	1	1	1	Harvest period
Blueberries							0.5	1	0.5				2
Cantaloupe								0.5	0.5				1
Grapes									1	0.5			1.5
Raspberries							1		1				2
Strawberries						0.5	0.5						1
Watermelon								0.5	1				1.5
Beans (green)							0.5	1	0.5				2
Broccoli and Cauliflower							1	1	1	1	0.5		4.5
Cabbage	1						1	0.5		0.5	1	1	5
Carrots	1	1	1	0.5			1	1	1	1	1	0.5	9
Cucumber							0.5	1	0.5				2
Leeks	1	1	1	1	1			0.5	1	1	1	1	9.5
Lettuce					1	1	1	1	1	1			6
Onion	1	1	1	1	1	1	1	1	1	1	1	1	12
Peas						0.5			0.5	0.5			1.5
Peppers (bell)							0.5	1	1	1			3.5
Squash							0.5	1	0.5				2
Spinach					0.5	0.5			0.5	1	0.5		3
Tomato								1	1	0.5			2.5
Turnip	1	1	1	1	0.5	1			1	1	1	1	9.5

Harvest map (hoop-houses)													
1= field fresh													
2 = hoop-house	January	February	march	April	May	June	July	August	Septemb	October	Novembe	December	
	1	1	1	1	1	1	1	1	1	1	1	1	Harvest period
Blueberries							0.5	1	0.5				2
Cantaloupe							0.5	1	0.5				2
Grapes									1	0.5			1.5
Raspberries							1		1	1			3
Strawberries						0.5	1	1	1	1			4.5
Watermelon								0.5	1				1.5
Beans (green)						1	1	1	1	0.5			4.5
Broccoli and Cauliflower							1	1	1	1	0.5		4.5
Cabbage	1	1	1				1	0.5		0.5	1	1	7
Carrots	1	1	1	0.5	1	0.5	1	1	1	1	1	1	11
Cucumber						0.5	1	1	0.5				3
Leeks	1	1	1	1	1			0.5	1	1	1	1	9.5
Lettuce					1	1	1	1	1	1	1	1	8
Onion	1	1	1	1	1	1	1	1	1	1	1	1	12
Peas						0.5			0.5	0.5			1.5
Peppers (bell)						0.5	1	1	1	1	1		5.5
Squash						1	1	1	1	1			5
Spinach	1	1	1	1	1	0.5			0.5	1	1	1	9
Tomato						0.5	1	1	1	1	0.5		5
Turnip	1	1	1	1	1	1			1	1	1	1	10

B.8 Hoop-house yield extension and storage

The crop cycles, type of crop (multi or continuous harvest, e.g. tomato, versus single harvest, e.g. lettuce) and harvest table were used to determine how the annual yields (see B.1) would change for hoop-house growing. For single harvest crops, yield was increased when another harvest was possible, for continuous harvesting crops, yield was increased proportionally (according to interview with hoop-house farmer).

Type	**Crop**	**Yield extension**	**Justification**
Fruits	Blueberries	None	
	Cantaloupe	1	It was assumed that they can only grow in hoop-houses in European climate
	Grapes	None	
	Raspberries	None	
	Strawberries	None	
	Watermelon	1	It was assumed that they can only grow in hoop-houses in European climate
Vegetable	Green beans	2	Double output https://www.growveg.co.uk/guides/quick-maturing-plants-5-fast-growing-vegetables-to-try/
	Broccoli and Cauliflower	None	
	Cabbage	1.0	No growth in winter, non-refrigeration storage considered
	Carrots	1.33	Additional harvest possible but smaller varieties, e.g. baby carrots https://www.growveg.co.uk/guides/quick-maturing-plants-5-fast-growing-vegetables-to-try/ non-refrigeration storage considered
	Cucumber	None	
	Leeks	None	non-refrigeration storage considered
	Lettuce	1.33	4th harvest possible
	Onions	None	non-refrigeration storage considered
	Peas	None	
	Peppers (bell)	1.5	3rd harvest possible, continuous harvesting character https://harvesttotable.com/vegetable_harvest_times/
	Squash	1.5	Double production but smaller varieties, 'Yellow Crookneck', 'Early Prolific Straightneck' or 'Raven' - https://www.hgtv.com/outdoors/gardens/garden-styles-and-types/vegetables-you-can-grow-in-two-months-or-less-pictures
	Spinach	2.0	Multiple harvests, no growth in winter
	Tomato	1.5	Continuous harvesting characteristic
	Turnip	None	non-refrigeration storage considered

B.9 Table of nutrient content of crops for hydroponics

The following values were used together with the recovery loss ratio to determine the nutrient requirements for hydroponic growing.

Type	Crop	N	P	K	Source
Fruit	Strawberries	0.00288	0.000448	0.00216	(Health Canada, 2005)
	Watermelon	0.0024	0.00032	0.00248	(Health Canada, 2005)
Vegetable	Cabbage	0.0023	0.00033	0.0027	(Fink et al., 1999)
	Cucumber	0.0017	0.0004	0.0028	(Fink et al., 1999)
	Lettuce	0.0018	0.0003	0.003	(Fink et al., 1999)
	Peppers (bell)	0.0020765	0.000315	0.002031	(Health Canada, 2005)

	Tomato	0.0027	0.0028	0.0076	(Health Canada, 2005)
	Turnip	0.00302	0.00056	0.0034	(Health Canada, 2005)

B.10 Fertilization rates for soil-based growing

Country	**Plant nutrient**	**Use per area of cropland (kg/ha)**	**Source**
United Kingdom	N	169.31	FAOSTAT 2015
	P	31.02	FAOSTAT 2015
	K	44.55	FAOSTAT 2015
France	N	113.44	FAOSTAT 2015
	P	22.01	FAOSTAT 2015
	K	24.73	FAOSTAT 2015

C. Climate curves and water requirements

It was found that typical datasets used (e.g. www.ceda.ac.uk, energyplus.net/weather) contain only hourly values of a specific single year, which might not be sufficiently representative. Therefore, part of this work was the generation of daily solar radiation and temperature profiles for both cities using WorldClim 30-year-average data (http://worldclim.org/version2) for an average day in each month (Fick and Hijmans 2017). Solar noon, average daily solar radiation, sunrise and sunset information, as well as minimum and maximum daily temperature values were used to construct the curves. It was assumed that solar radiation follows a positive sin curve profile and temperature was assumed to increase linearly from its minimum at sunrise with its maximum sometime after solar noon. WorldClim data provided temperature, rainfall and solar radiation, EnergyPlus provided the soil temperature (https://energyplus.net/weather-region/europe_wmo_region_6) and a solar calculator provided sunhours and solar noon (http://suncalc.net/). Daily evapotranspiration was obtained from an online calculator (http://www.engr.scu.edu/~emaurer/tools/calc_solar_cgi.pl) The solar radiation given in kJ/m^2/day on the surface was later converted to PAR by:

$$PAR\left(\frac{mol}{m^2 * day}\right) = \frac{SR\left(\frac{kJ(radiation}{m^2 * day}\right) * 0.45\left(\frac{J(radiation)}{J(PAR)}\right) * 1000\left(\frac{J}{kJ}\right)}{222000\left(\frac{J(PAR)}{mol}\right)}$$

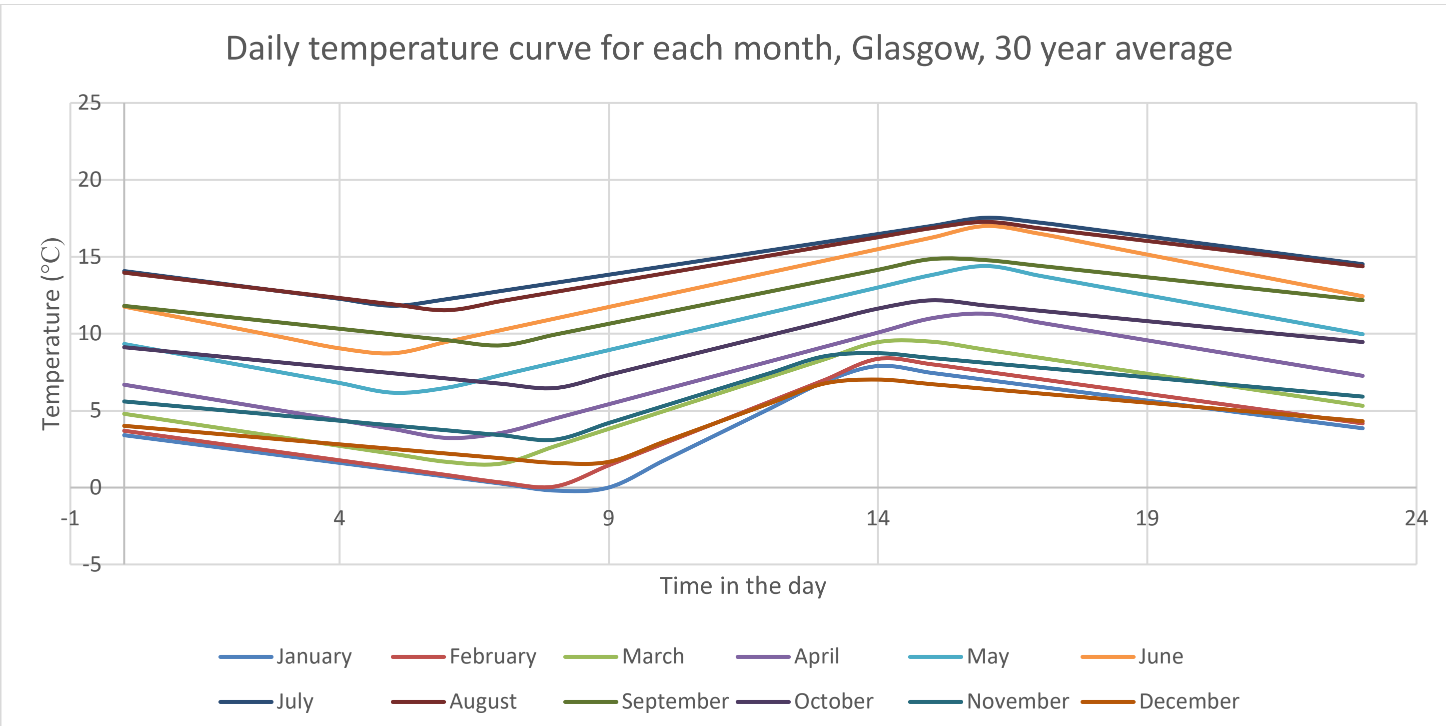
A positive sin-curve was used for the solar radiation (http://cliffmass.blogspot.com/2017/06/hottest-day-of-year-map.html) and the daily maximum calculated via Wolfram Alpha (http://www.wolframalpha.com). The temperature profile was linear, increased steadily after sunset to its maximum after solar noon (33% of the time between noon and sundown) and fell steadily again until sunset.

C.1 Rainfall data

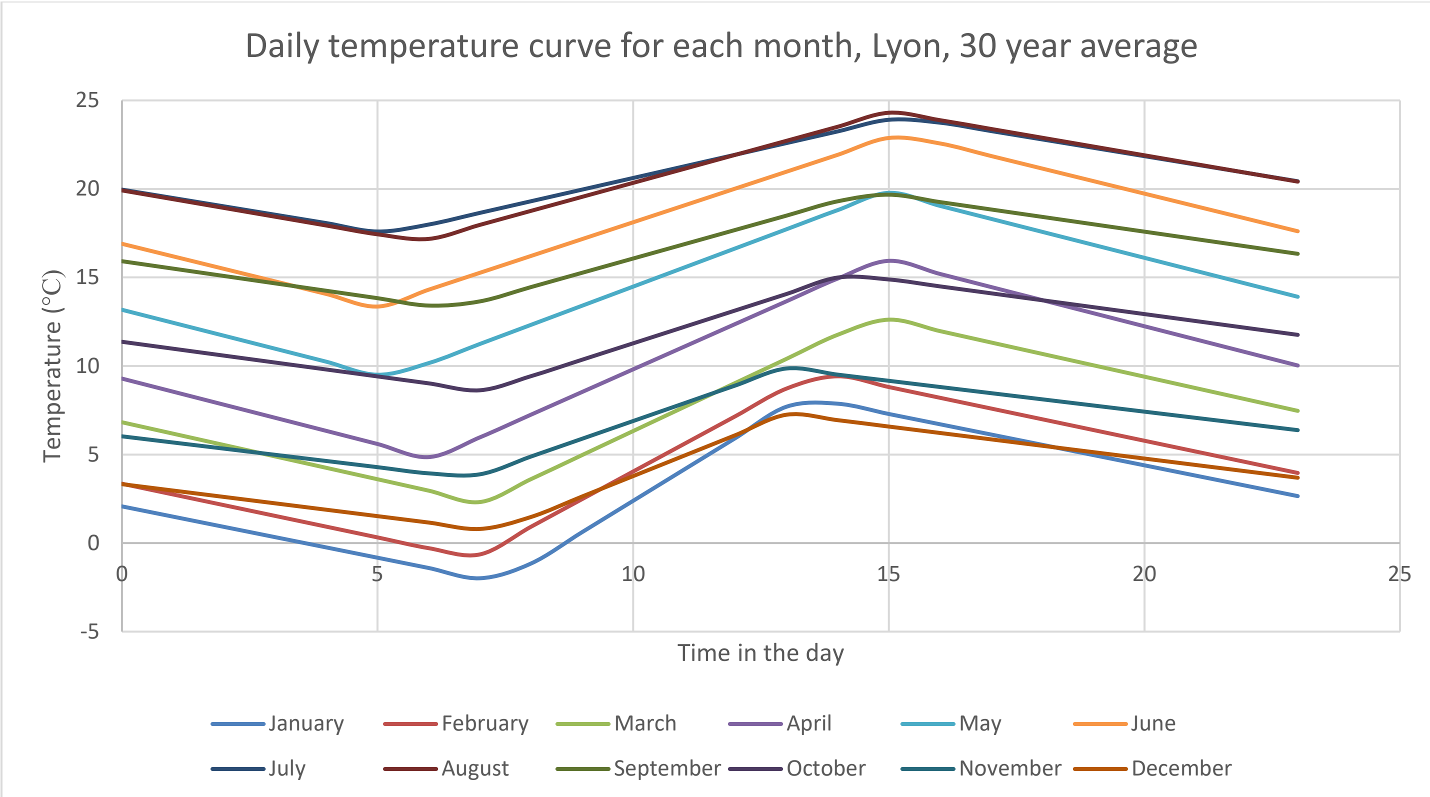
Month	Rainfall Glasgow (mm)	Rainfall Lyon (mm)	Average monthly evapotranspiration for Glasgow (mm/d)	Average monthly evapotranspiration for Lyon (mm/d)
January	154	54	2.4	4.84
February	106	53	4.58	7.06
March	116	55	7.86	10.07

April	65	73	12.02	13.51
May	71	87	15.33	16
June	67	79	16.97	17.14
July	75	61	16.32	16.67
August	91	69	13.57	14.67
September	125	87	9.6	11.52
October	146	95	5.78	8.17
November	43	75	3	5.46
December	141	56	1.92	4.31

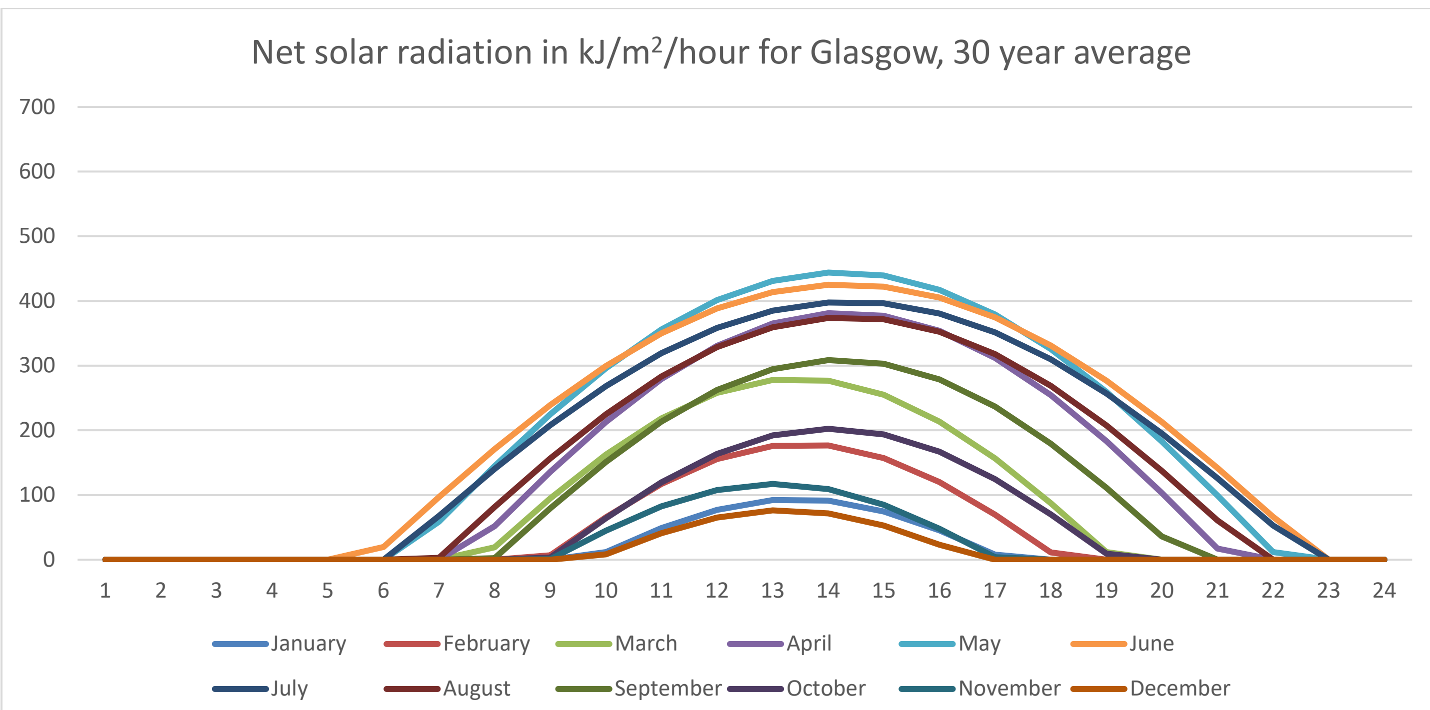
C.2 Temperature curves Glasgow



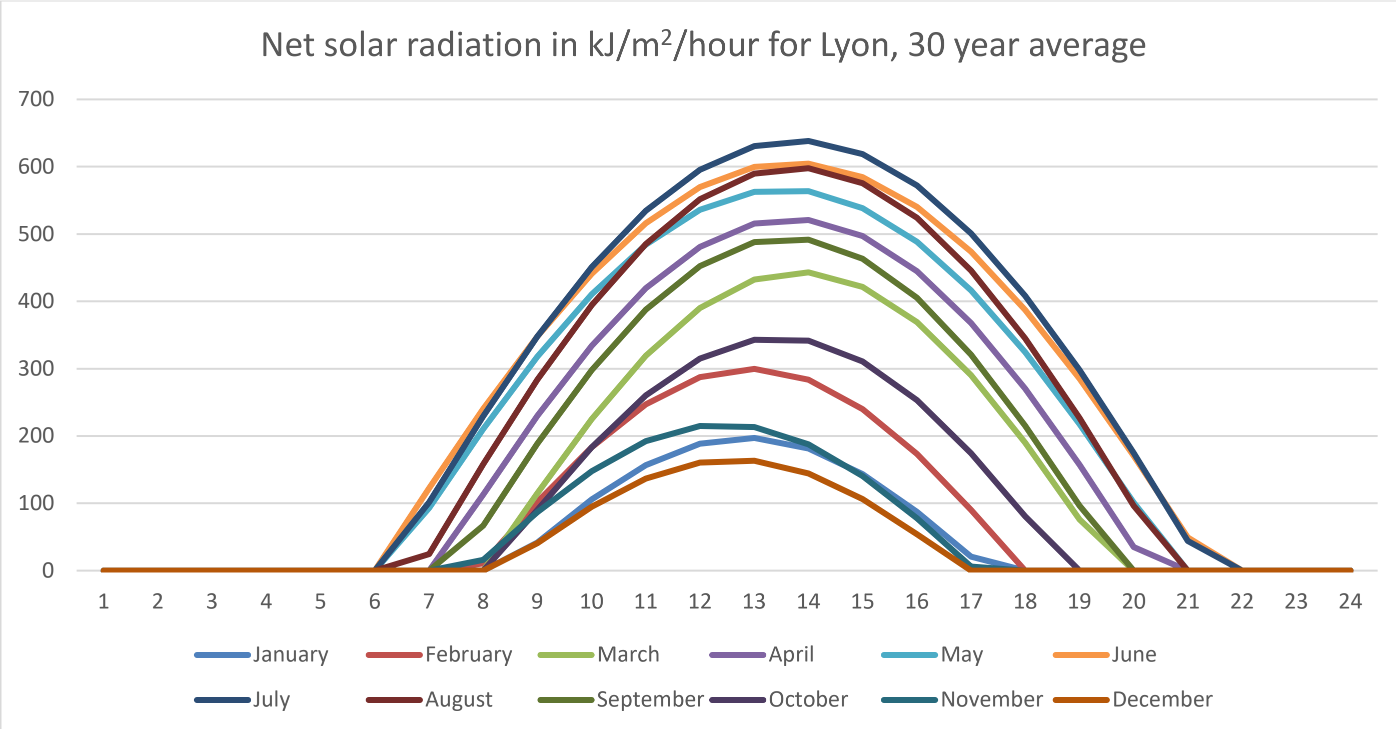
C.3 Temperature curves Lyon



C.4 Solar radiation curves Glasgow



C.5 Solar radiation curves Lyon



C.6 Irrigation and replenish water requirements

For soil-based growing, the harvest table and the crop cycles were used to determine whether the allocated area of a certain crop requires irrigation and gross irrigation water requirements were calculated according to Lupia et al. (2017), using evapotranspiration, temperature and local rainfall data (C.1 in SI).

For hydroponic growing, the water consumption was estimated according to the greenhouse evapotranspiration equations in Nadal et al. (2017b), employing monthly solar radiation data from WorldClim, and an artificial lighting factor according to the ratio of DLI supplied artificially versus naturally. It was assumed all transpired water is lost via ventilation and an additional 25% are required for humidification and spray cooling. For aquaponics, the water use was assumed to be 20 l/kg produce (Forchino et al., 2017).

D. Lighting and heating of greenhouses

D.1 Overview of equations

The lighting requirements were calculated using relation (1) and (2). It was assumed that the artificial lighting is supplied to each crop in order to be closer to their respective photoperiod (e.g. for a shorter period artificial lighting is supplied in the morning and late afternoon, for a longer period also at night)

$$DLI\_artificial = DLI\_req - DLI\_unblocked * transmissitivity * shading \tag{1}$$

$$Electricity\_req = molar\_efficacy * DLI\_artificial * growing\_area \tag{2}$$

The heating requirements were calculated according to the relations (3-7) which were found in Bakos, Fidanidis et al. (1999), the USDA Virtual Grower software (https://www.ars.usda.gov/midwest-area/wooster-oh/application-technology-research/docs/virtual-grower/). Losses through the cover were considered through walls and roof (see (8)), solar influx only through the roof, and exchanges with soil and roof (constant temperature assumed) only through the floor. Only the productive area within a greenhouse was considered for the evaporative losses.

$$Q_{cover} = K_{cover} * A_{cover} * \Delta T * Coefficient_{radiation} \quad (3)$$

$$Q_{solar} = Radiation * shading * \tau_{cover} * A_{greenhouse} \quad (4)$$

$$Qventing = C_{air} * Volume_{greenhouse} * n_{air\_changes} * \Delta T \quad (5)$$

$$Q_{floor} = K_{floor} * A_{greenhouse} * \Delta T \quad (6)$$

$$Q_{Evap} = \Delta H_{water} * \rho_{water} * A_{crops} * ET_0 * shading \quad (7)$$

$$A_{cover} = A_{greenhouse} + \sqrt{\left(A_{greenhouse} / number_{greenhouses}\right)} * 4 * height * number_{greenhouses} \quad (8)$$

D.2 Overview of heating and lighting related parameter

Parameter	Value	Source
K-value for polycarbonate greenhouse walls (K_{cover})	2.27 W / m^2 / K	Proksch 2016
Solar transmittance of cover (τ_{cover})	0.835	(Nadal et al., 2017)
Shading effect (shading)	0.9	(Shen et al., 2018)
Air replacements per hour (n_{air_change})	0.5	(Harbick & Albright, 2016)
Temperature set in greenhouse	24 °C (7 AM – 7 PM) and 16 °C (7 PM – 7 AM)	(Nadal et al., 2017)
Greenhouse height	3 m	Assumption
Coefficient radiation	1.2	Kirtsitis 1982
Specific heat capacity of air (C_{air})	0.837 kJ/m^3/K	(Bakos et al., 1999)
K-value soil (K_{floor})	0.34 W/m^2/K	(Papadakis & Kyritsis, 1989)
K-value roof (K_{floor})	0.525 W/m^2/K	(Castleton et al., 2010)
Temperature roof of host building	20 °C	Assumption, to calculate heat flow to and from host building
Enthalpy water (ΔH_{water})	2450 kJ/kg	N/A
Density water (ρ_{water})	1000 kg/m^3	N/A
Typical space heating France	134 kWh/m^2/annum	https://www.ovoenergy.com/guides/energy-guides/how-much-heating-energy-do-you-use.html
Typical space heating UK	133 kWh/m^2/annum	https://www.ovoenergy.com/guides/energy-guides/how-much-heating-energy-do-you-use.html
PAR transmittance of cover	0.7	(Proksch, 2016)
LED molar efficacy	8.33 mol/kWh	(Philips, 2018)
Rainwater harvesting efficiency	0.7 (hoop-houses), 0.9 (high-tech greenhouses)	(Angrill et al., 2012)
Application efficiency of irrigation	0.45 (surface, community), 0.9 (drip, intensive)	(Lupia et al.,2017)

The space heating was distributed according to the figure below from Vallati et al. (2015).

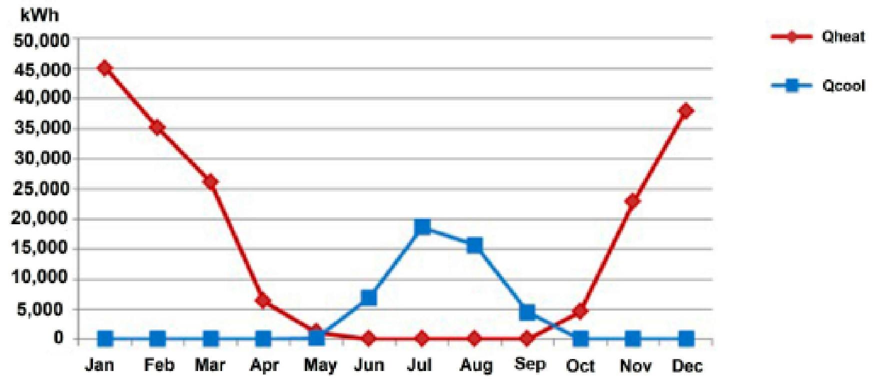


Figure 1. Yearly trend of energy demand for heating (Q heat) and cooling (Q cool), obtained with TRNSYS.

E. Process and waste parameter

E.1 Waste stream composition

Waste stream	Total carbon	Total nitrogen	Total phosphorus	Potassium	Dry matter	Source
Food waste	48.3% of dry mass	0.9%	0.22%	0.3%	27.7%	(Banks et al., 2011; Chiew et al., 2015)
Green waste	34.78% of dry mass	0.95%	0.15%	0.73%	30.6%	(Hertel et al., 2015) https://www.sruc.ac.uk/downloads/file/1276/tn650_optimising_the_application_of_bulky_organic_fertilisers
Insect compost	31.2% of dry mass	1.49%	0.98%	1.03%	74.3%	(Salomone et al., 2017)

As the yard waste is generated mostly in summer and fall and fertilizer needs to be mainly applied in spring and in fall for the next season, the annual generation and fertigation requirements were split up between the months according to assumptions (for fertilizer) and actual collection data (yard waste, http://publications.gc.ca/site/eng/436856/publication.html).

E.2 Annual profiles - generation of yard waste and fertilization

Month	Share of generated yard waste (%)	Share of fertigation needs (%)
January	0	0
February	0	5
March	1	20
April	4	20
May	17.5	15
June	16.5	5
July	16	5
August	15	5
September	11	10
October	12	10
November	6	5
December	1	0

E.3 Process considerations

Composting: Mass loss during composting (e.g. compaction) and carbon and nitrogen losses were calculated. High-throughput screw-driven institutional compost units with thermophilic bacteria were considered with a residence time of 1 month and without further operational inputs (www.ridan.co.uk).

Insect rearing: The process parameters include bioconversion on a wet basis, compost substrate output and composition, electricity requirements, larvae moisture content and required inputs of hatching compost, water and natural gas.

Anaerobic digestion: Employed parameters were biogas production and composition, dilution water, hydraulic residence time, volumetric yield, process heat (incl. pasteurization) as well as parasitic electricity for the plant (crushing, solid-liquid separation, conveying, control)(Banks et al., 2011). It was assumed that all input nutrients are in the digestate (Møller, Boldrin, and Christensen 2009), that biogas is desulfurized and dewatered (no consumables considered for these steps due to high capacity and regeneration potential of adsorbents), and that when the CHP units were off, the generated biogas was upgraded and fed into the grid for energy credit and all heat was provided via natural gas boilers. Surplus biogas was assumed to be upgraded on-site to biomethane via water-scrubbing and compression to 8 bar. It was assumed that organic fertilizer products have a lower nutrient availability when used in soil than chemical fertilizer. The semi-central treatment of digestate for final disposal was assumed to occur in 5 km average distance and either in a succession of membrane filtration steps (liquor) or a belt-press (fiber).

E.4 Overview of process parameters

The table below lists all process parameter that were used for the waste valorization. The composition of the compost, the whole digestate, the digestate liquor and fiber and their concentrates was dynamically adapted according to the inputs into composting and AD.

Aspect	Parameter	Value	Source
Anaerobic digestion	Additional feed water	0.3786 l /kg feed	(Banks et al., 2011)
	AD – biogas potential	156 Nm3/tonne food waste & 78 Nm3/tonne green waste	(Banks et al., 2011; Hertel et al., 2015)
	AD – biogas composition	62.7% CH_4, 34.8% CO_2, 2.5% H_2O	(Banks et al., 2011)
	Total solids – digestate	5%	Assumption based on (Dimambro, 2015)
	Total solids - fiber	32.62%	Based on mass balance and TS split according to (Eriksson & Runevad, 2016)
	Total solids - liquor	2.27%	Based on mass balance and TS split according to (Eriksson & Runevad, 2016)
	Volumetric yield	1.59 Nm3 biogas/m3/day	(Banks et al., 2011)
	Parasitic electricity requirements	59.112 kWh/tonne waste	(Banks et al., 2011)
	Parasitic heating requirements	0.11 kWh / kg feed	(Banks et al., 2011)
	CHP heat generation	12.12 kWh / Nm3 biogas	50% thermal efficiency (Walker et al., 2017)
	CHP electricity generation	1.68 kWh/Nm3 biogas	(Walker et al., 2017)
	CHP parasitary electricity	0.042 kWh/kWh produced	(Banks et al., 2011)

	Lower calorific value of biogas and natural gas	23 and 37 MJ/Nm3 biogas	(Møller etl al., 2009) (Walker et al., 2017)
	AD – biogas upgrading efficiency	95.2%	(Nock et al., 2014)
	Nutrient availability – fiber	50% N, 100% P, 100% K	(Chiew et al., 2015)
	Electricity consumption decanter centrifuge	4 kWh/m3 digestate	(Drosg et al., 2015), density was assumed to be 1000 kg/m3 due to the high water content
	Liquor content as share of original content in digestate	Mass: 91%, TS: 42%, TC: 35%, TN: 76%, TP: 38%, K: 91%	TS is total solids, TC is total carbon, TN is total nitrogen, TP is total phosphorus, K is Potassium (Eriksson & Runevad, 2016)(Drosg et al., 2015), fibre content according to mass balance (e.g. for total solids, 58%)
Secondary treatment	TS in concentrate (Ultrafiltration and reverse osmosis for liquor)	25%	(Rehl & Müller, 2011)
	TS in concentrate (Belt press for fiber)	90%	(NNFCC, 2016)
	Electricity consumption belt press	635 kWh/m3 feed	(NNFCC, 2016)
	Electricity consumption liquor membrane filtration	20.5 kWh/m3 feed	(WRAP, 2012)
	Density liquor	1000 kg/m3	Assumed same as water
	Density fiber	620 kg/m3	(WRAP, 2012)
Insect rearing	Insect bioconversion	17.5% (mass conversion from feed to larvae; the latter contains a moisture content of 62.4)	http://enterrafeed.com, (Salomone et al., 2017)
	Insect compost production	35% of feed	(Joly, 2018)
	Water use	61.1 l / tonne waste	(Salomone et al., 2017)
	Area use	45 m2 / tonne waste	(Joly, 2018)
	Natural gas use	20 l / tonne waste	(Joly, 2018)
	Electricity use	12.9 kWh/ tonne waste	(Salomone et al., 2017)
Composting	Compaction	63% mass loss	(Andersen et al., 2011)
	Composting - gaseous losses	55% of N, 69% of C	(Andersen et al., 2011; Eklind & Kirchmann, 2000)
	N2 loss as N	97.615%	(Cobo et al., 2018)
	N2O loss as N	1.400%	(Cobo et al., 2018)
	NH3 loss as N	0.985%	(Cobo et al., 2018)
	CO2 loss as C	95.0%	(Andersen et al., 2011)
	CH4 loss as C	3.9%	(Andersen et al., 2011)
	CO loss as C	0.08%	(Andersen et al., 2011)
	Processing capacity	14.25 $kg/m^3/day$	www.ridan.co.uk
	Nutrient availability – compost	17.5% N, 50% P, 100% K	(Chiew et al., 2015; Wielemaker, Weijma, & Zeeman, 2018)
	Density finished compost	650 kg/m3	Assumption
Aquaponics	Water use	20 l/kg fish	(Forchino et al., 2017)
	Tank density	30 kg/m^3	(Forchino et al., 2017)
	Growth period - carp	10 months	(FAO, 2014)
	Growth period – Catfish	9.5 months	(FAO, 2014)
	Growth period – Tilapia	7 months	(FAO, 2014)

	Feed ratio	50 kg/month/m^2	(FAO, 2014)
	Feed conversion ratio - Carp	1.6	(Fry et al., 2016)
	Feed conversion ratio - Catfish	1.3	(Fry et al., 2016)
	Feed conversion ratio - Tilapia	1.6	(Fry et al., 2016)
	Electricity use	10.1 kWh/m3/year	(Forchino et al., 2017)
Equipment (other)	Electricity use irrigation pumps – intensive farming	0.2432 kWh/m3	(Smajstrla et al., 2002)
	Hydroponics control and conveyance	0.1778 kWh/kg/year	(Barbosa et al., 2015)

It was assumed that H3PO4 is added to the digestate before solid-liquid separation to prevent volatilization of NH3 by reducing the pH value. The calculated amount was insignificant and therefore the amount and impact not considered. The composition of the insect compost and food and green waste was assumed constant and is listed in E.1.

F. Emissions

The carbon footprint of produce is given for the national supply, EU25 and rest of the world (RoW). The values for the UK, EU25 and RoW were obtained from Audsley et al. (2009), accounting for all related activities until reaching the distribution center. The values for France were taken from the Ecoinvent, Agribalyse and Agri Footprint databases at farm gate level. To account for logistics to the distribution center, it was assumed that the average transport distance is 200 km with a 21t truck, as calculated in Watkiss (2009) with an additional 0.13 kg CO2/kg produce. Due to data limitation, it was assumed that onions and leeks as well as parsnips and carrots have the same carbon footprint.

It was found that the countries of origin and their import quantity for a certain crop were similar for France and the UK, most likely since countries in Europe specialize on certain crops and have established distribution networks. Thus, the import emissions values for France were assumed to be the same but adjusted for shorter averages distances to the countries of origin. This was done by using half of the value determined by Webb et al. (2013) for the UK, i.e. 0.15 kg CO2/kg produce. Rest of the world usually meant import from Asia or Latin America, which was assumed to result in the same emissions for both countries.

F.1 Food emissions, domestic and import

Type	**Crop**	**Emissions domestic supply UK (kg CO2/kg produce)**	**Emissions domestic supply France (kg CO2/kg produce)**	**Emissions EU25 (kg CO2/kg produce)**	**Emissions RoW (kg CO2/kg produce)**
Fruits	Blueberries	0.84	0.84		1.39
	Cantaloupe	NA	0.375	1.55	1.74
	Grapes	NA	0.461	0.42	0.75
	Raspberries	0.84	0.84	0.95	
	Strawberries	0.84	0.991	1.06	
	Watermelon	NA	0.375	1.33	1.33
Vegetable	Green beans	1.55	0.427		10.7

	Broccoli and Cauliflower	1.94	0.455	2.22	
	Cabbage	0.22	0.427	0.48	
	Carrots	0.35	0.202	0.46	
	Cucumber	3.79	3.78	1.30	
	Leeks	0.37	0.265	0.48	
	Lettuce	1.15	0.311	1	
	Onions	0.37	0.265	0.48	
	Peas	0.29	0.286	0.4	
	Peppers (bell)	5.88	2.97	3.12	
	Squash	NA (0.323)	0.323	2.22	
	Spinach	NA (0.3535)	0.3535	2.22	
	Tomato	3.79	2.39	1.3	
	Turnip	0.35	0.202	0.46	

The carbon footprint of fish supply from aquaculture was calculated by accounting emissions of aquaculture production (incl. all feed related emissions) and an adaption factor for distribution (Ziegler et al., 2003). The carbon footprint of feed was calculated by accounting emissions of production (incl. growing and processing but excl. on-farm feed related emissions) and to-farm transport. It was assumed that 25% of the feed is soy meal and 75% are other feed components with a footprint as listed below. All other constant emissions factors and values are listed in the subsequent table.

F.2 Emissions of fish production and feed supply

Type	**Supply emission**	**Feed emission**	**Sources**
Carp	2.12 kg CO_2/kg * 1.124	1.08 kg CO_2/kg (75%)	(Robb et al., 2017)
Catfish	1.61 kg CO_2/kg * 1. 124	1.09 kg CO_2/kg (75%)	(Robb et al., 2017)
Tilapia	1.81 kg CO_2/kg * 1. 124	1.12 kg CO_2/kg (75%)	(Robb et al., 2017)
Soy meal		1.7 kg CO_2/kg (25%)	(Salomone et al., 2017)

F.3 Emission parameters

Type	**Parameter**	**Emission value**	**Sources**
Fertilizer	Production N (hydroponics use)	0.680 kg CO_2-eq / kg N	Calcium Nitrate (Fertilizers Europe, 2014)
	Production P (hydroponics use)	0.542 kg CO_2-eq / kg P	(Møller et al. 2009)
	Production K (hydroponics use)	0.417 kg CO_2-eq / kg K	(Møller et al. 2009)
	Production and application N	8.9 kg CO_2-eq / kg N	(Møller et al. 2009)
	Production and application P	1.8 kg CO_2-eq / kg P	(Møller et al. 2009)
	Production and application K	0.96 kg CO_2-eq / kg K	(Møller et al. 2009)
Emissions factors	Natural gas grid – France	0.27 kg CO_2 / kWh	(Møller et al. 2009)
	Natural gas grid – UK	0.204 kg CO_2 / kWh	(DECC, 2011)
	Electricity grid – France	0.0604 kg CO_2 / kWh	http://www.compareyourcountry.org/climate-policies?cr=oecd&lg=en&page=2

	Electricity grid – UK	0.410 kg CO_2 / kWh	(DECC, 2011)
	Diesel emissions	3.15 kg CO2 / l diesel	(Møller et al. 2009)
	Diesel use	0.03 l / tonne / km	(Møller et al. 2009)
	Water provision	0.15 kg CO_2 / m^3	(Møller et al. 2009)
	Biogas combustion	1.816842627 kg CO2/kg biogas	Based on mass balance
	Replacement natural gas (production)	0.052 kg CO_2/kWh	(Exergia, 2015)
Greenhouse gas equivalents	CH_4	25 kg CO2/kg	https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator
	N_2O	298 kg CO2/kg	https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator
	NH_3	2.11 kg CO2/kg	https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator
	CO	1.57 kg CO2/kg	https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

F.4 Formula for incineration

To account for different emissions based on the feed stream type and composition, the results from Astrup et al. (2009) were used to create an empiric equation that accounts not just for the total mass but also the carbon content.

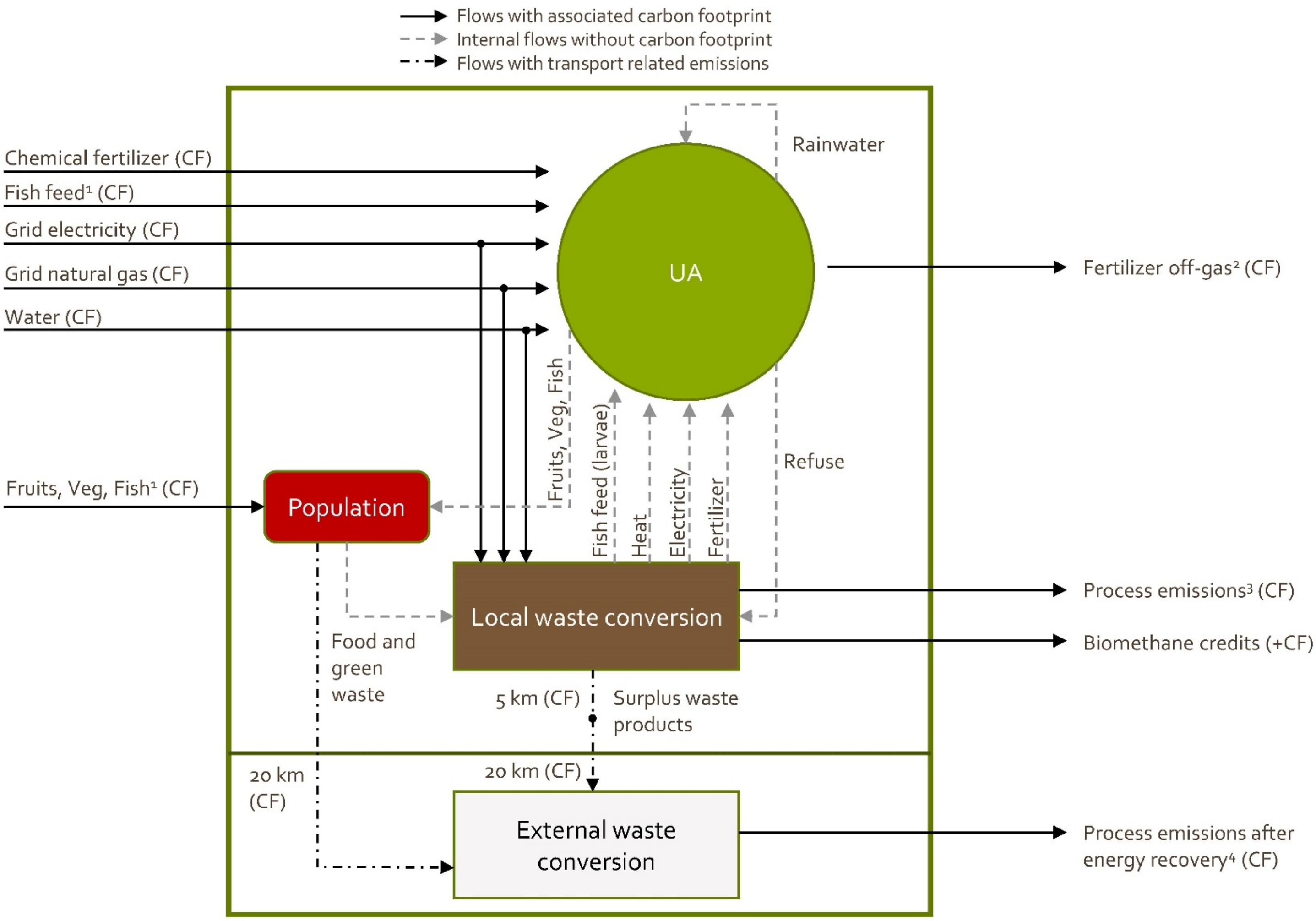
$$CO2_{incineration} = (0.014 - 0.619 * \text{Footprint}_{\text{Electricity}} * 4/10 * \text{mass}_{\text{carbon}} / \text{mass}_{\text{total}} / 0.15) * \text{mass}_{\text{total}} + 44/12 * \text{mass}_{\text{Carbon}}$$

The first term relates to the equipment use per unit weight, the following parameter describe the energy recovery benefit (the first term is the heat recovered per unit weight (kWh/kg), the second term the national footprint of electricity production, 4/10 is the ratio of heating values, the third term the amount of carbon and 0.15 the reference share of organic biogenic carbon used in the study to obtain the indicated energy benefit) and the final term describes the general emissions caused by the combustion.

The emissions for windrow composting were calculated based on the gaseous losses describes in the parameter table in SI E.3.

F.5 System boundary overview for carbon footprint accounting

This figure visualizes the flows considered which either were accounted via their associated carbon footprint (CF) (incoming and outgoing flows, transport emissions) or were internal flows which had no incurred emissions but which affected the flows across the boundary by substitution (e.g. local production of fertilizer reduces the need for externally supplied fertilizer). Biomethane credits across the boundary are marked with a + symbol as these had a beneficial carbon impact.

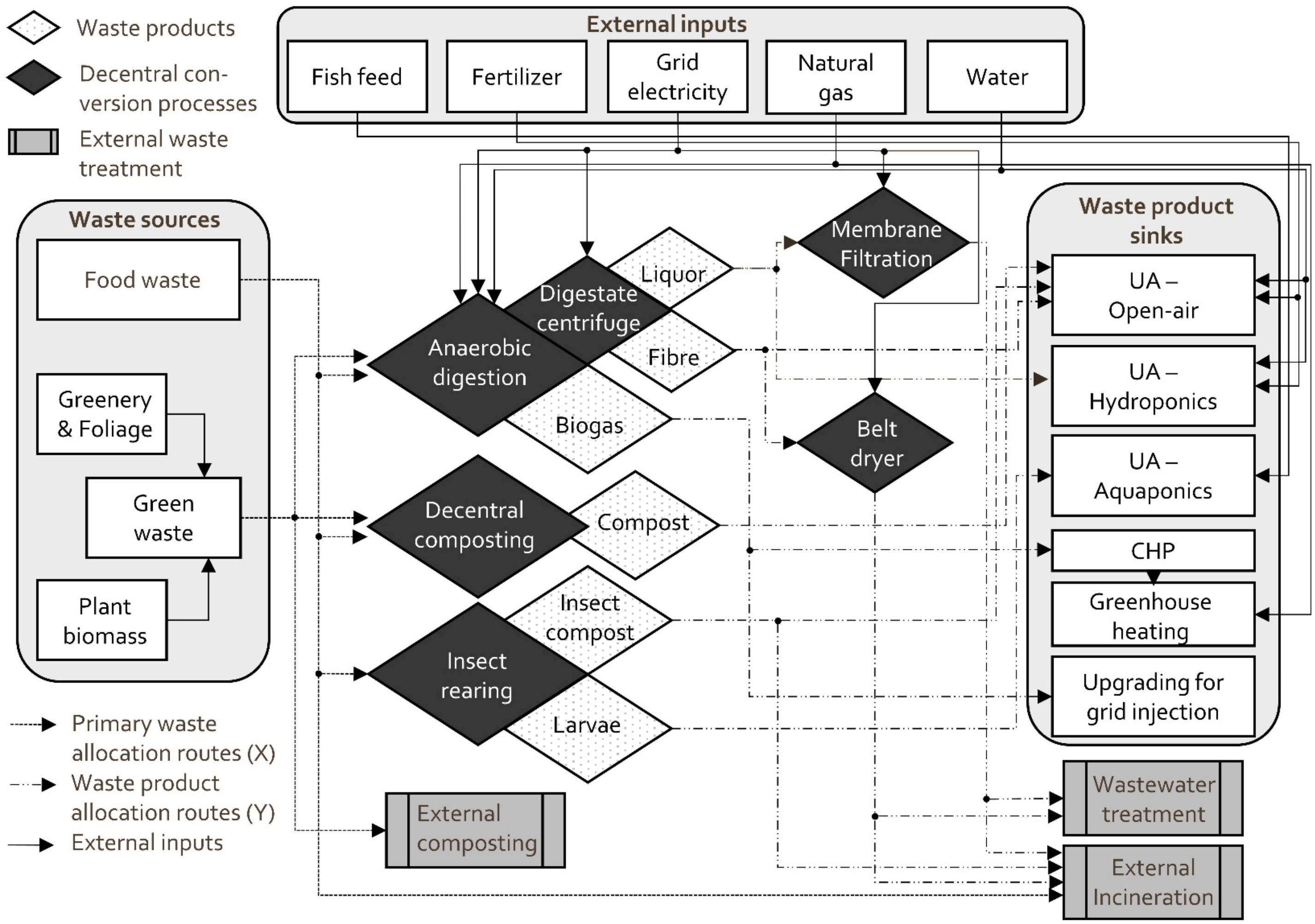


1 Emissions including production, inputs (e.g. water, fertilizer) and transport up to regional distribution center
2 Both for chemical fertilizer and organic fertilizer (compost and digestate fibre)
3 Includes biogas combustion and gaseous compost emissions
4 Includes gaseous compost emissions, operations of incineration plant, combustion of biogenic carbon, energy recovered

G. Optimization

The optimization routine used the resource nexus as superstructure, illustrated in the following schematic. The external or secondary treatment of surplus waste products through either membrane filtration of a belt dryer leads to two waste streams, waste water (which goes into the sewage and waste water treatment) and dried concentrate (which is incinerated).

G.1 Superstructure



G.2 Mathematical formulation

The decision variables were the allocation of food and green waste to the different waste conversion technologies (all X's) and the allocation of waste product to UA (the Y's).

$$X_m^{i,j} \in [0,1]$$
$$Y_m^{k} \in [0,1]$$

$$i \in \{Food\_waste, Green\_waste\}$$
$$j \in \{AD, Insect\_rearing, dec\_composting, external\_composting, external\_incineration\}$$
$$k \in \{Insect\_compost, Fibre, Liquor\}$$

Besides the constraints described in the main paper, all waste had to be allocated and the waste products were either allocated to UA practices or had to be centrally treated.

□

$$X_m^{FW,AD} + X_m^{FW,Ins} + X_m^{FW,C} + X_m^{FW,CI} = 1$$
$$X_m^{GW,AD} + X_m^{GW,C} + X_m^{GW,CC} = 1$$

The following equations ensured that all nutrient requirements were met and no overfertilization occurs, and no more insect larvae is produced than required as feed for aquaponics production:

$$Fert_{n,m}^{Ext,soil} = Fert_{n,m}^{Req Soil} - Y_m^{Fibre} * Fibre_{n,m} * A_n^{Fibre} - (Y_m^{insC} * C_{n,m}^{Ins} + C_{n,m}^{Compost}) * A_n^{compost}$$
$$Fert_{n,m}^{Ext,HP} = Fert_{n,m}^{Req.HP} - Y_m^{Liquor} * Liquor_{n,m} * A_n^{Recovery}$$

$$Feed_m^{Ext} + Feed_m^{Larvae} = Feed_m^{Req}$$

The hourly heat balance and monthly electricity balance determined the additional input required from the grid.

$$Q_{t,m}^{Ext} + I_{t,m}^{CHP} * Q_{t,m}^{Bio} + (1 - I_{t,m}^{CHP}) * Q_{t,m}^{Bio} * Z_{t,m}^{Injection} = Q_{t,m}^{GBG} + Q_{t,m}^{RTG} + Q_{t,m}^{AD}$$

$$P_m^{Ext} + \sum_{t \in T}^{t} I_{t,m}^{CHP} * 30.5 * Z^{CHP} = (1 - Y_m^{Fibre}) * Fibre_m^{Mass} * Z^{Dryer}$$
$$+ (1 - Y_m^{Liquor}) * Liquor_m^{Mass} * Z^{Filtration} + (X_m^{FW,AD} * W_m^{FW} + X_m^{GW,AD} * W_m^{GW}) * Z^{AD}$$
$$+ X_m^{FW,Insc} * W_m^{FW} * Z^{Ins} + P_m^{Irr} + P_m^{GH-Light} + P_m^{GH-Ops}$$

$$t \in T, T = \{1,2,...24\}, m \in M, M = \{Jan, Feb, ..., Dec\}, n = \{N, P, K, Ca\}$$

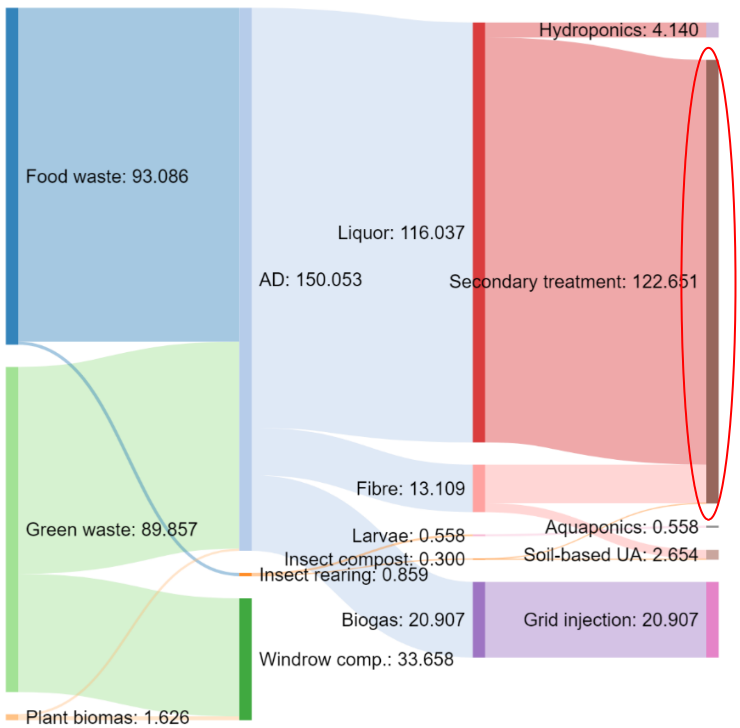
G.3 Nomenclature

Symbol	Variations	Meaning
X^{FW}	AD,Ins,C,CI	Share of food waste going into either of the conversion pathways
X^{GW}	AD,C,CC	Share of green waste going into either of the conversion pathways
Y	InsC,Fibre,Liquor	Share of waste product used in urban agriculture
Q	Ext, Bio, GBG ,RTG, AD	Heat flows (external, from biogas, ground-based greenhouses, rooftop greenhouses, anaerobic digestion)
I	CHP	Integer for CHP operation (0,1)
P	Ext, Irr, GH-Light, GH-ops	Electricity user or supply (grid, irrigation equipment, greenhouses)
Z	CHP, Dryer, Filtration, AD, Ins, Injection	Mass or throughput dependent electricity use factor for different conversion technologies
W	FW, GW	Amount of waste
Fert	Ext, Req / soil,HP	Amount of fertilizer
A	Fibre, compost, recovery	Plant availability or recovery loss factor
C	Ins, Compost	Amount of compost
Feed	Ext, Larvae, Req	Amount of fish feed
GWP	Gas, Power, Fert, Feed	Global warming potential factors

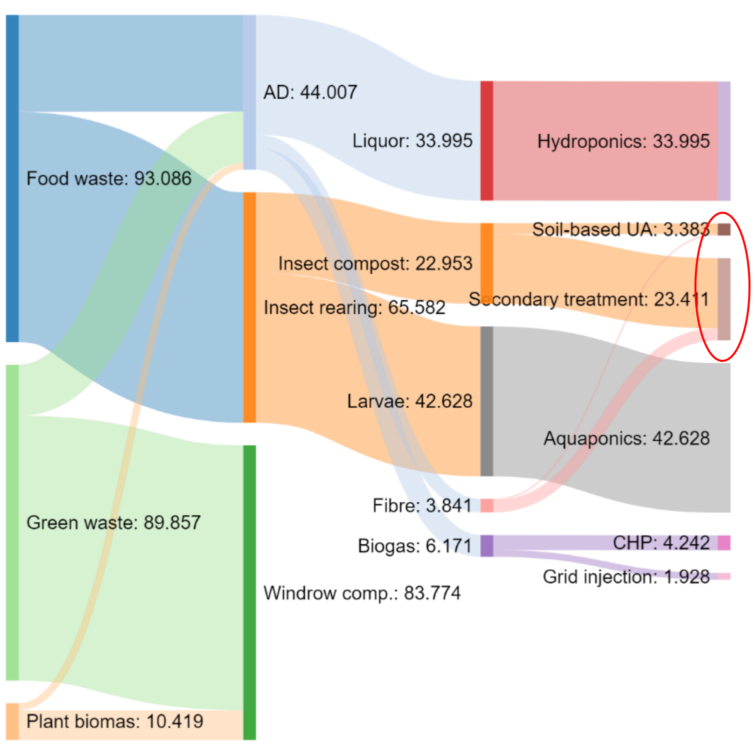
CO2	Other	gaseous emissions composting, incineration, digestate application, biogas burning

G.4 Mass flow without digestate constraint

The following two Sankey diagrams depict the mass flows for Glasgow at 0%and 100% ground-based greenhouses on large plots. Even in the case of 100% ground-based greenhouses and thus a higher sink potential, a large amount of digestate products have to undergo secondary treatment (even more so for Lyon). Hence the additional constraint of no decentral treatment of digestate liquor was introduced.



Mass flow after optimization in Glasgow for **0%** ground-based greenhouses on large plots

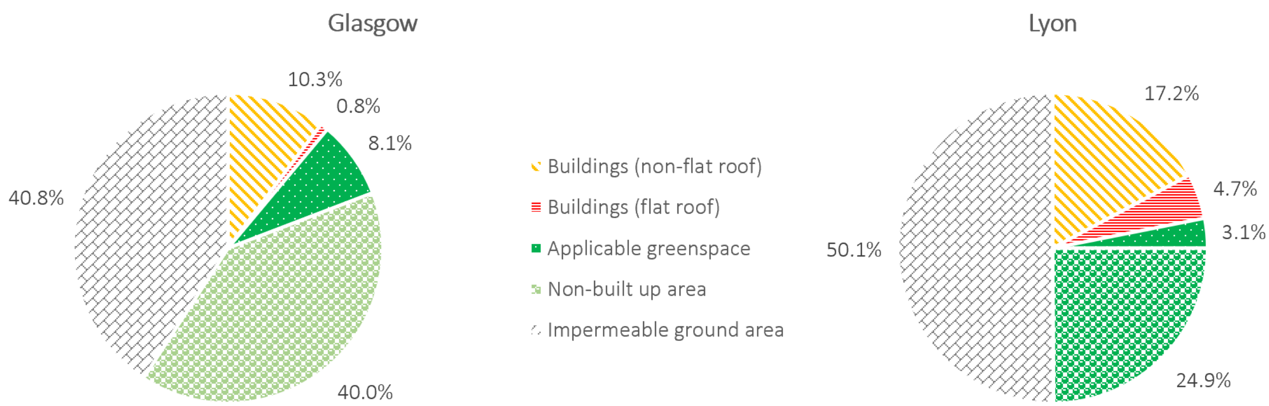


Mass flow after optimization in Glasgow for **100%** ground-based greenhouses on large plots

H.Discussion of results

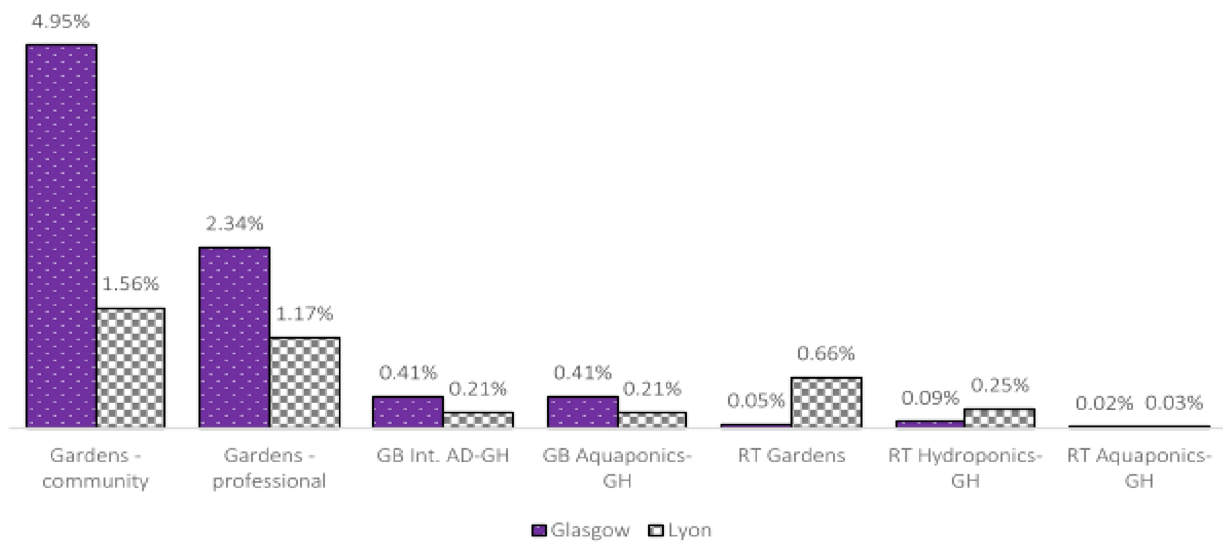
H.1 Spatial analysis

The figure below displays the split of areas for both cities as determined in ArcGIS Pro, with the size of the urban area being 47.98 km2 for Lyon and 186.86 km2 for Glasgow. Population-wise, the city of Lyon is almost twice as dense as Glasgow (6819 vs. 3560 people/km2), consequently the share of greenspaces and other non-built up area (e.g. waterways, trees) is smaller while buildings constitute a larger share. The relative share of flat roofs is much higher in Lyon (21.5% vs. 7.3%) while the relative share of applicable greenspaces is higher in Glasgow (20.3% versus 12.4%).



H.2 Distribution of growing area for 20/80 ratio

The distribution of applicable green- and rooftop spaces are shown here as percentage of the total urban area. Community gardens (>25m2) in Glasgow use around 3 times more urban area than Lyon and around twice as much for professional gardens and ground-based (GB) greenhouses (GH), while rooftop (RT) growing is significantly more prominent in Lyon, in particular on smaller roofs (between 100 and 500 m2).



H.3 Comparison with other studies – Spatial analysis

The obtained share of applicable greenspace (3.1%) and flat rooftop area (4.7%) for Lyon is lower than in other studies looking at dense urban centers, e.g. for a district in Munich, 23.6% of the total area was identified as applicable growing spaces and 9.8% of total area as flat roofs while the share of total roof area was similar (Gondhalekar & Ramsauer, 2017). For the less built-up city of Glasgow, a comparable study was done for Boston, in which of the total urban area a share of 10% as greenspaces and 7.4% as flat rooftop area was considered applicable (versus 8.1% and 0.8% in Glasgow) (Saha & Eckelman, 2017). The difference can partly be explained by different architecture styles and urban layouts but also by more restrictions considered by the methodology in this work, e.g. taking into account the shape of the area, an assumption for a realistic maximal scale-up and subtraction of non-productive spaces within a garden. Both of the previous studies therefore predicted higher levels of self-sufficiency than the two urban areas in this work. From this first study that simulates the production of a range of crops with multiple growing practices on a monthly basis, the results show nevertheless a still remarkable level of self-sufficiency, in particular for Glasgow. Many previous studies do not necessarily arrive at this outcome, which is sometimes due to consideration of only soil-based growing or the omission of rooftops spaces (Weidner et al., 2019). It should be noted that, within certain crop categories, it might not be desired to become fully dependent on urban produce, as extreme climate events or earthquakes would constitute severe supply risks.

H.4 Comparison with other studies – Resource requirements

Benis et al. (2017b) have simulated tomato production in a rooftop greenhouse in Paris with a similar climate to Lyon and obtained a heating intensity of 233 kWh/m2 and a lighting intensity of 93 kWh/m2 (versus 252 kWh/m2 and 143 kWh/m2 in this study). The heating intensity is comparable (Paris is slightly warmer). Another study has obtained a similar intensity for the south of France (240 kWh/m2)(Boulard et al., 2011). However, the lighting intensity for tomato production differs significantly, especially when considering that this work used DLI values for tomatoes of 13.5 mol/m2 PAR while Benis et al. (2017b) used 20 mol/m2 PAR, achieving roughly proportionally increased yields (42.9 versus up to 75 kg/m2) but also necessitating more supplemental lighting. The assumed shading and transmissivity losses in this work might contribute to, but does not fully explain, this large difference.

The net water use for hydroponic growing calculated in this work is slightly lower than in the comparable Paris study (28.3 l/kg versus 36 l/kg). Comparing the contributions to the carbon intensity of production, emissions calculated in this work are in a similar range as in other studies. Boulard et al. (2011) conducted an LCA analysis on heated greenhouses in the south of France and found the contribution of heating to CO2e emissions to be around 1.6 kg CO2e/kg tomato (versus 1.57 CO2e/kg in this work).

Goldstein et al. (2017) have assessed the amount of organic waste avoided if food waste compost is used in urban agriculture and the per-capita greenhouse gases for fruits, vegetables and nuts in both the current system and a soil-based UA system. The first metric relates to the waste assimilation investigated in this study. They found that for a population of 617,000 people, 9% of municipal organic solid waste (12,000 ton/a) could be assimilated when using 28.8% of Boston's urban space (125.4 km^2) as greenspaces and 1.3% as rooftops in the subtractive scenario. In their "Nutrition (-)" scenario, this leads to a self-sufficiency of 100% for vegetables. This may be compared to the 0% GH scenario in Glasgow, where 2.6% of organic waste is assimilated and 31.4% self-sufficiency is reached. Hence, for a self-sufficiency of 100%, around 8.3% organic waste would be assimilated, which is not too different in this work. The second metric, which is given in kg CO_2eq/capita/annum, relates to the produce emissions for the "UA+Ext" scenario at 0% GH. In their work, the baseline footprint for the category "fruits,veg, nuts" is around 200 kg while this work arrives at around 125 kg

CO2 eq./capita/annum. This may be explained by the fact that exotic fruits and nuts are included in their study. It is not possible to compare the carbon footprints of urban produce accurately as they have done a full LCA study on their crops while in this study only emissions from irrigation and fertigation have been accounted for urban open-air produce. Further, from the data provided in their SI, the footprint varies widely between crops and farms. For example, the average carbon footprint for tomato in this work is 0.091 kg CO_2eq/kg produce while in their work it ranges from 0.104 to 0.134 kg CO_2eq/kg produce for open plot farming and 0.625 kg CO_2eq/kg produce for open rooftop farming.

H.5 Additional insights about difference between the two cities

Note on Section 3.2: The relative carbon footprint of the "integrated" and "UA+Ext" versus the "current" scenario is much more favourable in Lyon, mainly due to the low carbon intensity of the electricity used for supplemental lighting. The carbon footprint benefit of the "integrated" over the "UA+Ext" scenario is more pronounced in Lyon than Glasgow as the latter has much more growing area and heating requirements which are far exceeding the energy provided by biogas, thus the relative effect of local energy utilization is reduced (more details in section 3.3.5). For Glasgow, the initial waste assimilation (with 0% greenhouses on larger ground plots) is almost zero as gardens need much less nutrients than greenhouses, and greenhouses on flat rooftops are very few (unlike in Lyon). This leads to initially similar carbon footprints for the "integrated" and "UA+Ext" scenarios in Glasgow.

Note on Section 3.3.1: This seasonal discrepancy is more pronounced in Glasgow where in relative terms less high-intensity greenhouse growing is applied.

Note on Section 3.3.2: For Glasgow, this (rainwater) surplus alone can cover the remaining water requirements for the whole system (water for AD and insect rearing operations, hoop-houses and open-air gardens). The CHPs are operated more often in Glasgow due to the colder climate. Since more organic waste fertilizer is used in Glasgow for both hydroponic and soil-based UA, the P-recovery is higher than in the Lyon.

Note on Section 3.3.3.: Glasgow assimilates more primary waste, both in absolute and relative terms, due to the larger sink capacity represented by aquaponic and hydroponic greenhouse area. Glasgow generates more green waste in total due to its larger share of non-built up space. Further, the comparatively higher volume of primary waste going to insect rearing than in Lyon is due to a higher ratio of aquaponics (acting as insect larvae sinks) vs. hydroponics (acting as digestate liquor sinks), compared to Lyon; the lower ratio in Lyon is caused by it having a range of smaller rooftop greenhouses. The use of waste products in soil-based UA is more pronounced in Glasgow due to a much greater garden area. Since the share of food waste into AD is higher in Lyon than Glasgow, more biogas is produced in Lyon per kg of waste, increasing the amount of biogas injected into the grid.

Note on Section 3.3.4: Together with the greater requirements for artificial lighting in Glasgow compared with Lyon, much higher emissions for grid electricity use are incurred.

Besides the carbon intensity of the electricity grid, a few other factors contribute to this difference: In Glasgow, the share of imported food with a larger carbon footprint is higher than in Lyon (57.4% versus 37.6%, respectively), the heating and lighting requirements are greater due to less solar radiation and lower temperatures, and the total output of emissions-intense greenhouse growing in winter is higher.

Note on Section 3.3.5: Due to the higher productivity relative to the waste assimilation (which is the waste accounted for in the "UA+Ext" scenario) and the lower associated emissions for incineration in Glasgow, the per-kg-produce emissions for waste are lower than in Lyon.

As less fibre has to undergo secondary treatment in relative terms in Glasgow, the benefit of the “integrated” scenario for emissions associated with waste is slightly higher in Glasgow than in Lyon.
On the other hand, Lyon benefits more from local use of heat due to the relationship between absolute heating requirements and absolute kWh of heat generated in the CHPs. Furthermore, the benefit of upgraded biogas provides a greater benefit for Lyon in relative terms, leading to an overall reduction of emissions related to external provision of natural gas of 1.53% for Glasgow and 4.63% for Lyon. The carbon balance for the “integrated” waste management from a 1 kg of food waste perspective is slightly better in Glasgow than in Lyon due to the larger share of primary waste going to the more favorable insect rearing route

Note on Section 4.1: In cities such as Lyon, with favorable climate and a large number of flat rooftops, enabling and facilitating the development of highly productive (rooftop) greenhouses seems a sensible strategy to increase self-sufficiency of fruit and vegetable supply. Further, a high-carbon electricity grid such in Glasgow currently means a high environmental price has to be paid for pure productivity.
Note on Section 4.2: The emissions intensity of the growing operations is heavily influenced by the climatic conditions (see table 2). A slight increase in PAR leads to a great reduction in artificial lighting requirements in the case of Lyon as it was closer to the optimum daily PAR value, favoring such sunnier locations. The influence of ambient temperature is less prominent but still significant, particularly on the heating requirements per unit area. Although in Glasgow more use is made of CHPs, Lyon benefits more from local use of heat due to the relationship between absolute heating requirements and absolute kWh of heat generated in the CHPs. The marginal benefit of heat utilization is thus smaller for greatly scaled-up UA & waste systems.

References

Andersen, J. K., Boldrin, A., Christensen, T. H., & Scheutz, C. (2011). Mass balances and life cycle inventory of home composting of organic waste. *Waste Management*, *31*(9–10), 1934–1942. https://doi.org/10.1016/j.wasman.2011.05.004

Angrill, S., Farreny, R., Gasol, C. M., Gabarrell, X., Viñolas, B., Josa, A., & Rieradevall, J. (2012). Environmental analysis of rainwater harvesting infrastructures in diffuse and compact urban models of Mediterranean climate. *International Journal of Life Cycle Assessment*, *17*(1), 25–42. https://doi.org/10.1007/s11367-011-0330-6

Astrup, T., Møller, J., & Fruergaard, T. (2009). Incineration and co-combustion of waste: Accounting of greenhouse gases and global warming contributions. *Waste Management and Research*, *27*(8), 789–799. https://doi.org/10.1177/0734242X09343774

Audsley, E., Brander, M., Chatterton, J., Murphy-Bokern, Webster, & Williams. (2009). *How Low can we go? An assessment of greenhouse gas emissions from the UK food system and the scope reduction by 2050*.

Bakos, G. C., Fidanidis, D., & Tsagas, N. F. (1999). Greenhouse heating using geothermal energy. *Geothermics*, *28*(6), 759–765. https://doi.org/10.1016/S0375-6505(99)00041-3

Banks, C. J., Chesshire, M., Heaven, S., & Arnold, R. (2011). Anaerobic digestion of source-segregated domestic food waste: Performance assessment by mass and energy balance. *Bioresource Technology*, *102*(2), 612–620. https://doi.org/10.1016/j.biortech.2010.08.005

Barbosa, G. L., Almeida Gadelha, F. D., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., … Halden, R. U. (2015). Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. Conventional agricultural methods. *International Journal of Environmental Research and Public Health*, *12*(6), 6879–6891. https://doi.org/10.3390/ijerph120606879

Benis, K., Reinhart, C., & Ferrão, P. (2017). Building-Integrated Agriculture (BIA) In Urban Contexts: Testing A Simulation-Based Decision Support Workflow. *Journal of Cleaner Production*, *147*(August), 589–602. https://doi.org/10.1016/j.jclepro.2017.01.130

Boulard, T., Raeppel, C., Brun, R., Lecompte, F., Hayer, F., Carmassi, G., & Gaillard, G. (2011). Environmental impact of greenhouse tomato production in France. *Agronomy for Sustainable Development*, *31*(4), 757–777. https://doi.org/10.1007/s13593-011-0031-3

Castleton, H. F., Stovin, V., Beck, S. B. M., & Davison, J. B. (2010). Green roofs; Building energy savings and the potential for retrofit. *Energy and Buildings*, *42*(10), 1582–1591. https://doi.org/10.1016/j.enbuild.2010.05.004

Chiew, Y. L., Spångberg, J., Baky, A., Hansson, P. A., & Jönsson, H. (2015). Environmental impact of recycling digested food waste as a fertilizer in agriculture - A case study. *Resources, Conservation and Recycling*, *95*(2015), 1–14. https://doi.org/10.1016/j.resconrec.2014.11.015

Cobo, S., Dominguez-Ramos, A., & Irabien, A. (2018). Trade-Offs between Nutrient Circularity and Environmental Impacts in the Management of Organic Waste. *Environmental Science and Technology*, *52*, 10923–10933. research-article. https://doi.org/10.1021/acs.est.8b01590

Colasanti, K., & Hamm, M. W. (2010). Assessing the local food supply capacity of Detroit, Michigan. *Journal of Agriculture, Food Systems, and Community Development*, *1*(2), 41–58. https://doi.org/10.5304/jafscd.2010.012.002

DECC. (2011). *Anaerobic Digestion Strategy and Action Plan A commitment to increasing energy from waste through Anaerobic Digestion*.

Dimambro, M. E. (2015). Novel uses for digestate : Protected horticulture. In *20th European Biosolids & Organic Resources Conference & Exhibition*. Manchester.

Drosg, B., Fuchs, W., Al Seadi, T., Madsen, M., & Linke, B. (2015). *Nutrient Recovery by Biogas Digestate Processing*. *IEA Bioenergy*. https://doi.org/10.13140/rg.2.1.3182.6403

Eklind, Y., & Kirchmann, H. (2000). Composting and storage of organic household waste with different litter amendments. II: Nitrogen turnover and losses. *Bioresource Technology*, *74*(2), 125–133. https://doi.org/10.1016/S0960-8524(00)00005-5

Eriksson, L., & Runevad, D. (2016). *Evaluating digestate processing methods at Linköping biogas plant*.

Linkoeping University.
Exergia. (2015). *Study on Actual GHG Data for Diesel, Petrol, Kerosene and Natural Gas*.
FAO. (2014). *Small-scale aquaponic food production*.
Fertilizers Europe. (2014). *Carbon footprint reference values. Energy efficiency and greenhouse gas emissions*.
Fesquet, V. (2015). Vertical Farming , from utopia to a business model Recent developments, (March).
Fink, M., Feller, C., Scharpf, H. C., Weier, U., Maync, A., Ziegler, J., … Strohmeyer, K. (1999). Nitrogen, phosphorus, potassium and magnesium contents of field vegetables - Recent data for fertiliser recommendations and nutrient balances. *Journal of Plant Nutrition and Soil Science*, *162*(1), 71–73. https://doi.org/10.1002/(SICI)1522-2624(199901)162:1<71::AID-JPLN71>3.0.CO;2-0
Forchino, A. A., Lourguioui, H., Brigolin, D., & Pastres, R. (2017). Aquaponics and sustainability: The comparison of two different aquaponic techniques using the Life Cycle Assessment (LCA). *Aquacultural Engineering*, *77*, 80–88. https://doi.org/10.1016/j.aquaeng.2017.03.002
Fry, J. P., Love, D. C., MacDonald, G. K., West, P. C., Engstrom, P. M., Nachman, K. E., & Lawrence, R. S. (2016). Environmental health impacts of feeding crops to farmed fish. *Environment International*, *91*, 201–214. https://doi.org/10.1016/j.envint.2016.02.022
Goldstein, B. P., Hauschild, M. Z., Fernández, J. E., & Birkved, M. (2017). Contributions of Local Farming to Urban Sustainability in the Northeast United States. *Environmental Science and Technology*, *51*(13), 7340–7349. https://doi.org/10.1021/acs.est.7b01011
Gondhalekar, D., & Ramsauer, T. (2017). Urban Climate Nexus City : Operationalizing the urban Water-Energy-Food Nexus for climate change adaptation in Munich , Germany. *Urban Climate*, *19*, 28–40. https://doi.org/10.1016/j.uclim.2016.11.004
Haberman, D., Gillies, L., Canter, A., Rinner, V., Pancrazi, L., & Martellozzo, F. (2014). The Potential of Urban Agriculture in Montréal: A Quantitative Assessment. *ISPRS International Journal of Geo-Information*, *3*(3), 1101–1117. https://doi.org/10.3390/ijgi3031101
Harbick, K., & Albright, L. D. (2016). Comparison of energy consumption: Greenhouses and plant factories. *Acta Horticulturae*, *1134*, 285–292. https://doi.org/10.17660/ActaHortic.2016.1134.38
Health Canada. (2005). Nutrient Value of Some Common Foods. *Canadian Nutrient File*, 1–54.
Hertel, S., Navarro, P., Deegener, S., & Körner, I. (2015). Biogas and nutrients from blackwater, lawn cuttings and grease trap residues???experiments for Hamburg???s Jenfelder Au district. *Energy, Sustainability and Society*, *5*(1). https://doi.org/10.1186/s13705-015-0057-5
Joly, G. (2018). *Valorising Organic Waste using the Black Soldier Fly (Hermetia illucens), in Ghana*. KTH Royal Institue of Technology, Stockholm.
KZNDARD. (n.d.). Length of growing period: Retrieved November 26, 2018, from https://www.kzndard.gov.za/images/Documents/Horticulture/Veg_prod/length_of_growing_period.pdf
Lupia, F., Baiocchi, V., Lelo, K., & Pulighe, G. (2017). Exploring Rooftop Rainwater Harvesting Potential for Food Production in Urban Areas. *Agriculture*, *7*(6), 46. https://doi.org/10.3390/agriculture7060046
Møller, J., Boldrin, A., & Christensen, T. H. (2009). Anaerobic digestion and digestate use: Accounting of greenhouse gases and global warming contribution. *Waste Management and Research*, *27*(8), 813–824. https://doi.org/10.1177/0734242X09344876
Nadal, A., Alamús, R., Pipia, L., Ruiz, A., Corbera, J., Cuerva, E., … Josa, A. (2017). Urban planning and agriculture. Methodology for assessing rooftop greenhouse potential of non-residential areas using airborne sensors. *Science of the Total Environment*, *601–602*, 493–507. https://doi.org/10.1016/j.scitotenv.2017.03.214
Nadal, A., Llorach-Massana, P., Cuerva, E., López-Capel, E., Montero, J. I., Josa, A., … Royapoor, M. (2017). Building-integrated rooftop greenhouses: An energy and environmental assessment in the mediterranean context. *Applied Energy*, *187*, 338–351. https://doi.org/10.1016/j.apenergy.2016.11.051
NNFCC. (2016). *Assessment of digestate drying as an eligible heat use in the Renewable Heat Incentive*. York.
Nock, W. J., Walker, M., Kapoor, R., & Heaven, S. (2014). Modeling the water scrubbing process and energy requirements for CO 2 capture to upgrade biogas to biomethane. *Industrial and Engineering Chemistry Research*, *53*(32), 12783–12792. https://doi.org/10.1021/ie501280p
Orsini, F., Gasperi, D., Marchetti, L., Piovene, C., Draghetti, S., Ramazzotti, S., … Gianquinto, G. (2014). Exploring the production capacity of rooftop gardens (RTGs) in urban agriculture: the potential impact on

food and nutrition security, biodiversity and other ecosystem services in the city of Bologna. *Food Security*, *6*(6), 781–792. https://doi.org/10.1007/s12571-014-0389-6

Papadakis, G., & Kyritsis, S. (1989). Soil Energy Balance Analysis of a Solar Greenhouse, (January), 231–243.

Philips. (2018). GreenPower LED production module. Retrieved November 26, 2018, from http://images.philips.com/is/content/PhilipsConsumer/PDFDownloads/Global/Horticulture/ODLI20180418_001-UPD-en_AA-Brochure_Philips_Production_Module_International_EN.pdf

Rehl, T., & Müller, J. (2011). Life cycle assessment of biogas digestate processing technologies. *Resources, Conservation and Recycling*, *56*(1), 92–104. https://doi.org/10.1016/j.resconrec.2011.08.007

Robb, D. H. F., MacLeod, M., Hasan, M. R., & Soto, D. (2017). Greenhouse gas emissions from aquaculture: A life cycle assessment of three Asian systems. *FAO Fisheries and Aquaculture Technical Paper*, (609), I,III,IV,VIII,XI,XII,XIII,XIV,1-92. https://doi.org/10.1515/eko-2015-0009

Saha, M., & Eckelman, M. J. (2017). Growing fresh fruits and vegetables in an urban landscape: A geospatial assessment of ground level and rooftop urban agriculture potential in Boston, USA. *Landscape and Urban Planning*, *165*(August 2016), 130–141. https://doi.org/10.1016/j.landurbplan.2017.04.015

Salomone, R., Saija, G., Mondello, G., Giannetto, A., Fasulo, S., & Savastano, D. (2017). Environmental impact of food waste bioconversion by insects: Application of Life Cycle Assessment to process using Hermetia illucens. *Journal of Cleaner Production*, *140*, 890–905. https://doi.org/10.1016/j.jclepro.2016.06.154

Shao, Y., Heath, T., & Thu, Y. (2016). Developing an economic estimation system for vertical farms. *International Journal of Agricultural and Environmental Information Systems*, *7*(2).

Shen, Y., Wei, R., & Xu, L. (2018). Energy consumption prediction of a greenhouse and optimization of daily average temperature. *Energies*, *11*(1). https://doi.org/10.3390/en11010065

Smajstrla, A. G., Castro, B. F., & Clark, G. A. (2002). *Energy Requirements for Drip Irrigation of Tomatoes in North Florida*.

Vallati, A., Grignaffini, S., & Romagna, M. (2015). A New Method to Energy Saving in a Micro Grid. *Sustainability*, *7*(10), 13904–13919. https://doi.org/10.3390/su71013904

Walker, M., Theaker, H., Yaman, R., Poggio, D., Nimmo, W., Bywater, A., … Pourkashanian, M. (2017). Assessment of micro-scale anaerobic digestion for management of urban organic waste: A case study in London, UK. *Waste Management (New York, N.Y.)*, *61*, 258–268. https://doi.org/10.1016/j.wasman.2017.01.036

Watkiss, P. (2009). Comparative Life Cycle Assessment of Food Commodities Procured for UK Consumption through a Diversity of Supply Chains: Appendix 2. https://doi.org/10.1109/TELSKS.2003.1246180

Webb, J., Williams, A. G., Hope, E., Evans, D., & Moorhouse, E. (2013). Do foods imported into the UK have a greater environmental impact than the same foods produced within the UK? *International Journal of Life Cycle Assessment*, *18*(7), 1325–1343. https://doi.org/10.1007/s11367-013-0576-2

Weidner, T., Yang, A., & Hamm, M. W. (2019). Consolidating the current knowledge on urban agriculture in productive urban food systems: Learnings, gaps and outlook. *Journal of Cleaner Production*, *209*, 1637–1655. https://doi.org/10.1016/J.JCLEPRO.2018.11.004

Wielemaker, R. C., Weijma, J., & Zeeman, G. (2018). Harvest to harvest: Recovering nutrients with New Sanitation systems for reuse in Urban Agriculture. *Resources, Conservation and Recycling*, *128*, 426–437. https://doi.org/10.1016/j.resconrec.2016.09.015

WRAP. (2012). Enhancement and treatment of digestates from anaerobic digestion. *Waste and Resources Action Programme*, (May), 1–38. https://doi.org/10.1007/s11666-009-9304-7

Ziegler, F., Nilsson, P., Mattsson, B., & Walther, Y. (2003). Life Cycle assessment of frozen cod fillets including fishery-specific environmental impacts. *The International Journal of Life Cycle Assessment*, *8*(1), 39–47. https://doi.org/10.1007/BF02978747