# Sustainability assessment of urban rooftop farming using an interdisciplinary approach

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## Doctoral thesis

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A thesis submitted in fulfilment of the requirements for the Doctoral degree in Environmental Sciences and Technology

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# Sustainability assessment of urban rooftop farming using an interdisciplinary approach

by

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> “The universe does not behave
> according to our pre-conceived ideas.
> It continues to surprise us.”
> *Stephen Hawking*

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The present thesis entitled *Sustainability assessment of urban rooftop farming using an interdisciplinary approach* by Esther Sanyé Mengual has been carried out at the Institute of Environmental Science and Technology (ICTA) at Universitat Autònoma de Barcelona (UAB)

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Jordi

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# Abbreviations

| | |
|---|---|
| 1.4 DB eq. | 1.4 dichlorobenzene equivalent emissions |
| ADP | Abiotic depletion potential |
| ALO | Agricultural land occupation |
| AP | Acidification potential |
| CED | Cumulative energy demand |
| CLS | Current Linear System |
| $C_2H_4$ eq. | Ethylene equivalent emissions |
| CFC-11 eq. | Trichlorofluoromethane equivalent emissions |
| CML | Institute of Environmental Sciences (Leiden) |
| $CO_2$ | Carbon dioxide |
| $CO_2$ eq. | Carbon dioxide equivalent emissions |
| CSA | Community-supported agriculture |
| CTE | Spanish technical code of edification |
| DIY | Do-it-yourself |
| EEA | European Environment Agency |
| ELCD | European Reference Life Cycle Database |
| EP | Eutrophication potential |
| FAO | Food and agriculture organization of the United Nations |
| FD | Fossil depletion |
| FE | Freshwater eutrophication |
| FET | Freshwater ecotoxicity |
| FU | Functional unit |
| GHG | Greenhouse gas emissions |
| GIS | Geographic Information System |
| GR | Green roof |
| GWP | Global warming potential |
| HDPE | High density polyethylene |
| HTP | Human toxicity potential |
| ICTA | Institute of Environmental Science and Technology (UAB) |
| ILCD | International Reference Life Cycle Data System |
| IPCC | Intergovernmental Panel on Climate Change |
| IR | Ionising radiation |
| IRTA | Institute of Agriculture and Food Research and Technology |
| i-RTG | Integrated rooftop greenhouse |
| ISO | International Organization for Standardization |

| | |
|---|---|
| LCA | Life cycle assessment |
| LCC | Life cycle costing |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| LDPE | Light density polyethylene |
| ME | Marine eutrophication |
| MET | Marine ecotoxicity |
| MJ eq. | Mega joules equivalent |
| MRD | Mineral resources depletion |
| NFT | Nutrient film technique |
| NLT | Natural land transformation |
| ODP | Ozone layer depletion potential |
| PMF | Particular matter formation |
| POF | Photochemical oxidant formation |
| $PO_4^{-3}$ eq. | Phosphate equivalent emissions |
| PP | Polypropylene |
| PVC | Polyvinyl chloride |
| RF | Rooftop farming |
| RTG | Rooftop greenhouse |
| Sb eq. | Antimony equivalent emissions |
| SETAC | Society of Environmental Toxicology and Chemistry |
| $SO_2$ eq. | Sulphur dioxide equivalent emissions |
| Sostenipra | Sustainability and Environmental Prevention research group |
| TA | Terrestrial acidification |
| TC | Total cost |
| TET | Terrestrial ecotoxicity |
| TP | Total profit |
| UA | Urban agriculture |
| UAB | Universitat Autònoma de Barcelona |
| ULO | Urban land occupation |
| UNEP | United Nations Environmental Program |
| URF | Urban rooftop farming |
| VF | Vertical farming |
| WD | Water depletion |

# Acknowledgments from a life cycle perspective

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# Summary

Urban agriculture (UA) is blooming around cities of the developed world as a response to the increasing urban population, the growing environmental awareness of the industrial food system and the need of addressing social gaps. These new local food systems aims to develop sustainable pathways that re-establish the relations between producers and consumers while boosting local economies and minimising food-miles. Furthermore, the recent financial crisis and the spread of vacant lands have revitalised UA projects, not only at the self-managed level (i.e., community, private) but also at the commercial one. In particular, UA practitioners and farmers have found in the roofs of the city a vacant space for placing food production leading to the development of urban rooftop farming (URF). Consequently, rooftop farms, rooftop greenhouses and rooftop gardens have colonized buildings. Nevertheless, specific assessment of the potential implementation and the sustainability performance of different URF forms, cultivation techniques and crops, are necessary.

To address these gaps, this dissertation seeks to answer two main research questions "What is the potential of urban rooftop farming in qualitative and quantitative terms?" and "What are the environmental impacts and economic costs of urban rooftop farming systems?". With this goal, a methodological framework is proposed and three case studies are analysed, which are pilot experiences of different forms of urban rooftop farming.

Food production in cities is a complex system that involves several stakeholders, has multiple scales and affects the three dimensions of sustainability (environment, economy, society). Thus, a comprehensive assessment might combine different disciplines to approach such topic. This dissertation follows an interdisciplinary framework that includes (a) qualitative research, to deepen in the perceptions of the different stakeholders related to UA and URF; (b) geographic information systems (GIS), to identify and quantify the available and feasible roofs for implementing rooftop farming; (c) life cycle assessment (LCA), to quantify the environmental burdens of rooftop farming systems; and (d) life cycle costing (LCC), to quantify the economic costs of URF. This framework enables to approach URF from the city scale (e.g., planning perspective) to the system scale (e.g., food products).

A stakeholders' analysis through qualitative interviews unravelled that the development of rooftop farming in Barcelona is currently facing some limitations mainly due to a constrained support from some stakeholders. The main barriers to supporting urban rooftop farming are the lack of a common definition of urban agriculture, the specific origin of UA in Barcelona and its urban morphology and the limited social acceptance of some food production techniques. However, stakeholders valued the sustainability benefits (i.e., environmental, economic and social) linked to urban rooftop farming, particularly in the context of the development of a local green economy.

In quantitative terms, urban rooftop farming shows a great potential for increasing the current local production and reducing the environmental burdens of the city's "foodprint". A multicriteria set is needed to identify the technically and economically feasible roofs for the implementation of commercial rooftop greenhouses (RTGs) (i.e., availability of space, sunlight, resistance and slope, and legal and planning requirements). Industrial parks and retail parks are here analysed and compared. Retail parks show a greater short-term potential (53-98%) than industrial parks (8%) due to a more resistant architecture, although industrial parks are of great interest for large-scale URF implementation plans due their extensive area. The potential

implementation of integrated rooftop greenhouses (i-RTGs) which take advantage from the residual flows from the building (i.e., residual heat and $CO_2$, rainwater) is an innovative way of rooftop farming. Benefits of i-RTGs vary in warm regions (e.g., Mediterranean), where unheated production can be performed, and cold regions (e.g., The Netherlands), where greenhouses requires heating. The preference between regions for implementing i-RTGs is based, thus, on whether the goal is increasing food production (i.e., higher crop yields in warm areas) or reducing environmental burdens (i.e., substitution of energy consumption for heating in cold areas).

From a life cycle perspective, the rooftop greenhouse lab (RTG-Lab) (Bellaterra, Spain), the community rooftop garden in Via Gandusio (Bologna, Italy) and a private rooftop garden in the city centre of Barcelona (Spain) are analysed. URF can become an environmentally-friendly option for further develop urban agriculture and local food systems in cities. However, results depend on the type of rooftop farming, the crop and the growing system. The pilot projects assessed in this dissertation unravelled some trends and drawn some recommendations for the development of rooftop farming.

Regarding food production in rooftop greenhouses, the greenhouse structure plays a major role in the environmental impacts and the economic costs (41.0-79.5%), as in conventional agriculture. Although the greenhouse structure of RTGs have greater environmental impacts than multi-tunnel greenhouses (between 17 and 75 %), tomatoes from an RTG in Barcelona are more environmentally-friendly not only at the production point (between 9 and 26% lower) but also at the consumer (between 33 and 42 % lower). Although tomato production results in 21% higher cost than conventional tomatoes, the consideration of the entire supply-chain highlights the competitiveness of RTGs as local food systems.

Regarding rooftop gardens, crop inputs are the most contributing elements. The community garden employed re-used elements in their design (e.g., pallets) and irrigation was the most contributing stage (60-75%). In the private garden, fertirrigation (between 33 and 46%) and the structure of the garden (between 28 and 35%) (i.e., made of raw wood) were the main contributors. Rainwater harvesting for supplying the water demand of the crops and the integration of re-used elements in the cultivation structures might enhance the sustainability of gardens by decreasing the resources consumption of the system.

The comparison of different growing techniques in the community garden highlighted the higher eco-efficiency of soil production, when compared to hydroponic techniques (i.e., nutrient film technique, floating system). The assessment of different crops showed the same pattern in the community and private rooftop gardens. Fruit vegetables have lower environmental burdens than leafy vegetables since they yield better. However, these rooftop farming forms perform polyculture, the design of which is commonly oriented to fruit vegetables, resulting in a low plant density for leafy vegetables. An improved design, which divides the garden, could then improve and balance these divergences among crop types.

This dissertation contributes to the comprehension of the development process of competitive and sustainable urban agriculture and urban rooftop farming in cities of developed countries by developing methodological aspects and generating new data on the topic. The methods and results advance in the knowledge and understanding of rooftop farming, urban agriculture and local food in order to support decision-making processes in the design and development of future rooftop farming projects. Future research and strategies might focus on assessing the perceptions of stakeholders in other case studies, while focusing on specific aspects such as social acceptance; quantifying the potential of rooftop farming in other urban areas and cities; and assess more case studies and URF forms from a sustainability perspective, paying particular attention to the integration of the social aspects.

# Resumen

La agricultura urbana está floreciendo en las ciudades de países desarrollados como respuesta al aumento de población urbana, la creciente concienciación ambiental sobre el sistema industrial alimentario i la necesidad de resolver ciertas problemáticas sociales. Estos nuevos sistemas de producción local de alimentos tienen como objetivo desarrollar modelos sostenibles que restablezcan las relaciones entre productores y consumidores, a la vez que impulsan las economías locales y reducen el transporte asociado a los alimentos. Por otro lado, la reciente crisis económica y la expansión de espacios abandonados en las ciudades ha revitalizado los proyectos de agricultura urbana, no sólo a nivel de autogestión (comunitario, privado) sino también a nivel comercial. En particular, los nuevos profesionales y agricultores urbanos han encontrado en las terrazas y cubiertas de la ciudad un espacio vacío donde situar la producción de alimentos, dando lugar al desarrollo de la agricultura urbana en cubierta. Consecuentemente, granjas, invernaderos y jardines han colonizado las cubiertas de los edificios. No obstante, una evaluación específica de la potencial implementación y el perfil de sostenibilidad de las diferentes formas de agricultura urbana en cubierta.

En este contexto, la presente tesis trata de responder a dos preguntas de investigación: "¿Cuál es el potencial de la agricultura urbana en cubierta en términos cualitativos y cuantitativos?" y "¿Cuáles son los impactos ambientales y los costes económicos de las diferentes formas de agricultura urbana en cubierta?". Con este objetivo, se propone un marco metodológico y se analizan tres casos de estudio que son pruebas piloto de diferentes formas de agricultura urbana en cubierta.

La producción de alimentos en ciudades es un sistema complejo que implica varios actores sociales, tiene múltiples escalas y afecta a las tres dimensiones de la sostenibilidad (medio ambiente, economía y sociedad). Por lo tanto, una evaluación exhaustiva debe combinar varias disciplinas para abordar estos sistemas. Esta tesis sigue un marco interdisciplinar que incluye (a) investigación cualitativa, para profundizar en las percepciones de los diferentes actores sociales relacionados con la agricultura urbana y la agricultura urbana en cubierta; (b) sistemas de información geográfica (SIG), para identificar y cuantificar las cubiertas disponibles y viables para la implementación de la agricultura en cubierta; (c) el análisis de ciclo de vida (ACV), para la cuantificación de los impactos ambientales de los sistemas de agricultura en cubierta; y (d) el análisis de costes de ciclo de vida (ACCV), para cuantificar los costes económicos de la agricultura en cubierta. Este marco metodológico permite evaluar la agricultura urbana en cubierta des de la escala ciudad (por ejemplo, des de la perspectiva de planeamiento) a la escala sistema (por ejemplo, producto alimentario).

Un análisis de las percepciones de los distintos actores sociales a través de entrevistas cualitativas desveló que el desarrollo de la agricultura urbana en cubierta en Barcelona se enfrenta actualmente a ciertas limitaciones, principalmente a causa de la falta de apoyo de algunos actores. Las principales barreras son la falta de una definición común de agricultura urbana, el origen específico de la agricultura urbana en Barcelona y su morfología urbana, y la limitada aceptación social de algunas técnicas de cultivo. No obstante, los actores sociales valoran los beneficios sostenibles (ambientales, económicos y sociales) vinculados a la agricultura urbana en cubierta, en particular en el contexto del desarrollo de una economía verde local.

En términos cuantitativos, la agricultura urbana en cubierta muestra un gran potencial para aumentar la actual producción local de alimentos y reducir las cargas ambientales del flujo de

alimentos de la ciudad. Un conjunto de criterios es necesario para identificar las cubiertas técnica y económicamente viables para la implementación de invernaderos en cubierta comerciales: la disponibilidad de espacio, la luz solar, la resistencia y la pendiente, y los requisitos legales y de planificación. Los parques comerciales muestran un mayor potencial a corto plazo (53 a 98%) que los parques industriales (8%), debido a una arquitectura más resistente, aunque los parques industriales son de gran interés para un plan de implementación de agricultura urbana en cubierta a gran escala debido a su extensa área. La potencial implementación de invernaderos en cubierta integrados, los cuales aprovechan los flujos residuales del edificio (es decir, el calor y $CO_2$ residuales, agua de lluvia), es una forma innovadora de agricultura en cubierta. Los beneficios de estos sistemas varían en las regiones cálidas (por ejemplo, el Mediterráneo), donde la producción pasiva en invernaderos se puede realizar, y las regiones frías (por ejemplo, Países Bajos), donde los invernaderos requieren calefacción. La preferencia entre las regiones para la implementación de invernaderos integrados se basa, por tanto, en si el objetivo es aumentar la producción de alimentos (en zonas cálidas, la productividad puede aumentar) o reducir las cargas ambientales (es decir, en zonas frías, el consumo de energía para calefacción se puede sustituir).

Desde una perspectiva de ciclo de vida, la tesis analiza el invernadero en cubierta del Rooftop Greenhouse lab (RTG-Lab) (Bellaterra, España), el jardín comunitario en cubierta de Vía Gandusio (Bolonia, Italia) y un jardín privado en cubierta en el centro de Barcelona (España). La agricultura urbana en cubierta puede ser una opción sostenible para desarrollar la agricultura urbana y los sistemas alimentarios locales en las ciudades. Sin embargo, los resultados dependen de la forma de agricultura en cubierta, el tipo de cultivo y el sistema de cultivo. Los proyectos piloto evaluados en esta tesis muestran unas primeras tendencias, que permiten listar recomendaciones para el desarrollo de la agricultura en cubierta.

En cuanto a la producción de alimentos en invernaderos en cubierta, el propio invernadero es el principal elemento en los impactos ambientales (41,0-79,5%) y el coste económico (64%), como en la agricultura convencional. Aunque un invernadero en cubierta tiene mayores impactos ambientales (entre 17 y 75%) que un invernadero convencional, la producción de tomate en el RTG-Lab en Barcelona resultó tener menores impactos ambientales que un invernadero convencional, no sólo en finalizar la producción (entre 9 y 26% menor) sino también cuando llega al consumidor (entre 33 y 42% menor). En cuanto al coste económico, pese a que la producción de tomates en cubierta resulta un 21% más cara, cuando se considera toda la cadena de suministro convencional, se pone de manifiesto la competitividad de los invernaderos en cubierta como sistemas de producción local.

En cuanto a los jardines en cubierta, los consumos del cultivo (es decir, agua, fertilizantes, energía) tienen el papel más relevante. El jardín comunitario en cubierta emplea elementos reutilizados en su diseño (por ejemplo, pallets) y el riego fue la etapa más impactante (60-75%). En el jardín privado en cubierta, la fertirrigación (entre 33 y 46%) y la estructura del jardín (entre el 28 y el 35%) fueron los principales contribuyentes al impacto ambiental. La recolección de agua de lluvia para el suministro de la demanda de agua de los cultivos y la integración de elementos reutilizados en las estructuras de cultivo podrían aumentar la sostenibilidad de los jardines al disminuir el consumo de recursos del sistema.

La comparación de las diferentes técnicas de cultivo en el caso de estudio comunitario destacó la mayor eco-eficiencia de la producción en suelo, en comparación con las técnicas hidropónicas (es decir, la técnica de película de nutrientes, sistema flotante). La evaluación de los diferentes cultivos mostró el mismo patrón en los jardines en cubierta comunitario y privado. Los cultivos con fruto (por ejemplo, el tomate) tienen unos impactos ambientales más bajos que los cultivos de hoja (por ejemplo, la lechuga), ya que las productividades son más altas. Sin embargo, estas formas de agricultura en cubierta realizan policultivo, cuyo diseño está habitualmente orientado a las hortalizas de fruto dando lugar a una densidad de plantación más baja de la que se puede realizar para cultivos de hoja. Un diseño mejorado, que divide el jardín según cultivos, podría mejorar y equilibrar estas divergencias entre los tipos de cultivo.

Esta tesis contribuye a la comprensión del proceso de desarrollo de una agricultura urbana y agricultura urbana en cubierta competitiva y sostenible en las ciudades de los países desarrollados mediante el avance en aspectos metodológicos y la generación de nuevos datos sobre el tema. Los métodos y resultados amplían el conocimiento y la comprensión de la agricultura en cubierta, la agricultura urbana y la producción local de alimentos para dar apoyo a los procesos de toma de decisiones en el diseño y desarrollo de futuros proyectos de agricultura en cubierta. Futuras investigaciones deberían centrarse en la evaluación de las percepciones de los actores sociales en otras ciudades, focalizando en aspectos específicos como la aceptación social; en cuantificar el potencial de la agricultura en cubierta de otras áreas urbanas y ciudades; y en evaluar más casos de estudio y formas de agricultura urbana en cubierta desde una perspectiva de sostenibilidad, haciendo especial énfasis en la integración de los aspectos sociales.

# Resum

L'agricultura urbana està florint al voltant de les ciutats del món desenvolupat com a resposta a l'augment de població urbana, la creixent conscienciació ambiental entorn el sistema industrial d'aliments i la necessitat d'abordar problemàtiques socials. Aquests nous sistemes de producció local d'aliments tenen com a objectiu desenvolupar models sostenibles que restableixin les relacions entre productors i consumidors, alhora que impulsen les economies locals i redueixen el transport associat als aliments. D'altra banda, la recent crisi financera i l'expansió dels espais abandonats a les ciutats han revitalitzat els projectes d'agricultura urbana, no només a nivell d'autogestió (és a dir, de forma comunitària o privada), sinó també a nivell comercial. En particular, els nous professionals i els agricultors urbans han trobat en els terrats de la ciutat un espai buit on situar la producció d'aliments, donant lloc al desenvolupament de l'agricultura urbana en coberta. Conseqüentment, granges, hivernacles i jardins han colonitzat les cobertes dels edificis. No obstant, manca una avaluació específica de la potencial implementació i el perfil de sostenibilitat de les diferents formes d'agricultura urbana en coberta, tècniques de cultiu i cultius.

En aquest context, la present tesi tracta de respondre a dues preguntes d'investigació "Quin és el potencial de l'agricultura urbana en coberta en termes qualitatius i quantitatius?" i "Quins són els impactes ambientals i els costos econòmics de les diferents formes d'agricultura urbana en coberta?". Amb aquest objectiu, es proposa un marc metodològic i s'analitzen tres casos d'estudi que són experiències pilot de diferents formes d'agricultura urbana en coberta.

La producció d'aliments a les ciutats és un sistema complex que implica diversos actors socials, té múltiples escales i afecta les tres dimensions de la sostenibilitat (medi ambient, economia, societat). Per tant, una avaluació exhaustiva ha de combinar diferents disciplines per abordar aquests temes. Aquesta tesi segueix un marc interdisciplinari que inclou (a) investigació qualitativa, per aprofundir en les percepcions dels diferents actors socials relacionats amb l'agricultura urbana i l'agricultura en coberta; (b) sistemes d'informació geogràfica (SIG), per identificar i quantificar les cobertes disponibles i viables per a la implementació de l'agricultura en coberta; (c) l'anàlisi de cicle de vida (ACV), per quantificar les càrregues ambientals dels sistemes d'agricultura en coberta; i (d) l'anàlisi de costos de cicle de vida (ACCV), per quantificar els costos econòmics de l'agricultura en coberta. Aquest marc metodològic permet avaluar l'agricultura urbana en coberta des de l'escala ciutat (per exemple, perspectiva de planificació) a l'escala del sistema (per exemple, productes alimentaris).

Una anàlisi de la percepció dels diversos actors socials a través d'entrevistes qualitatives va desvetllar que el desenvolupament de l'agricultura en coberta a Barcelona s'enfronta actualment a algunes limitacions, principalment a causa de la manca de suport d'alguns actors. Les principals barreres per al suport a l'agricultura urbana en coberta són la manca d'una definició comuna de l'agricultura urbana, l'origen específic de l'agricultura urbana a Barcelona i la seva morfologia urbana i la limitada acceptació social d'algunes tècniques de producció d'aliments. No obstant això, els actors socials valoren els beneficis sostenibles (és a dir, ambiental, econòmica i social) vinculada a l'agricultura urbana en coberta, en particular en el context del desenvolupament d'una economia verda local.

En termes quantitatius, l'agricultura urbana en coberta mostra un gran potencial per augmentar l'actual producció local d'aliments i reduir les càrregues ambientals del flux d'aliments de la ciutat. Un conjunt de criteris múltiples és necessari per identificar els sostres tècnica i econòmicament viables per a la implementació d'hivernacles en coberta comercials (és a dir, la

disponibilitat d'espai, la llum solar, la resistència i la pendent, i els requisits legals i de planificació). Els parcs comercials mostren un major potencial a curt termini (53-98%) que els parcs industrials (8%), a causa d'una arquitectura més resistent, encara que els parcs industrials són de gran interès per a un pla d'implementació d'agricultura urbana en coberta a gran escala a causa de la seva àrea extensa. La potencial aplicació d'hivernacles en coberta integrats, els quals aprofiten els fluxos residuals de l'edifici (és a dir, la calor i $CO_2$ residuals, aigua de pluja), és una forma innovadora d'agricultura en coberta. Els beneficis d'aquests sistemes varien en les regions càlides (per exemple, el Mediterrani), on la producció passiva en hivernacle es pot realitzar, i les regions fredes (per exemple, Països Baixos), on els hivernacles requereixen calefacció. La preferència entre les regions per a l'aplicació d'hivernacles integrats es basa, per tant, en si l'objectiu és augmentar la producció d'aliments (en zones càlides, la productivitat pot augmentar) o reduir les càrregues ambientals (és a dir, en zones fredes, el consum d'energia per calefacció es pot substituir).

Des d'una perspectiva de cicle de vida, l'hivernacle en coberta del rooftop greenhouse lab (RTG-Lab) (Bellaterra, Espanya), el jardí comunitari en coberta de Via Gandusio (Bolonya, Itàlia) i un jardí privat en coberta al centre de Barcelona (Espanya) són analitzats. L'agricultura urbana en coberta pot esdevenir una opció ecològica per desenvolupar l'agricultura urbana i els sistemes alimentaris locals a les ciutats. No obstant això, els resultats depenen de la forma d'agricultura en coberta, el tipus de cultiu i el sistema de cultiu. Els projectes pilot avaluats en aquesta tesis mostren unes primeres tendències, que permeten llistar recomanacions per al desenvolupament de l'agricultura en coberta.

Pel que fa a la producció d'aliments en hivernacles en coberta, el propi hivernacle és el principal element en els impactes ambientals (41,0-79,5%) i els cost econòmic (64%), com en l'agricultura convencional. Tot i que un hivernacle en coberta té una majors impactes ambientals (entre 17 i 75%) que un hivernacle convencional, la producció de tomàquet en el RTG-Lab a Barcelona va resultar tenir un menor impacte ambientals que un hivernacle convencional, no només en finalitzar la producció (entre 9 i 26% menor) sinó també quan arriba al consumidor (entre 33 i 42% menor). En quant al cost econòmic, tot i que la producció de tomàquets en coberta resulta un 21% més cara, quan es considera tota la cadena de subministrament convencional, es posa de manifest la competitivitat dels hivernacles en coberta com a sistemes de producció local.

Pel que fa als jardins en coberta, els consums del cultiu (és a dir, aigua, fertilitzants, energia) tenen el paper més rellevant. El jardí comunitari en coberta empra elements reutilitzats en el seu disseny (per exemple, pallets) i el reg va ser l'etapa més impactant (60-75%). En el jardí privat en coberta, la fertirrigació (entre 33 i 46%) i l'estructura del jardí (entre el 28 i el 35%) van ser els principals contribuents al impacte ambiental. La recol·lecció d'aigua de pluja per al subministrament de la demanda d'aigua dels cultius i la integració d'elements reutilitzats en les estructures de cultiu podria augmentar la sostenibilitat dels jardins en disminuir el consum de recursos del sistema.

La comparació de les diferents tècniques de cultiu en el cas d'estudi comunitari va destacar la major eco-eficiència de la producció en sòl, en comparació amb les tècniques hidropòniques (és a dir, la tècnica de pel·lícula de nutrients, sistema flotant). L'avaluació dels diferents cultius va mostrar el mateix patró en els jardins en coberta comunitari i privat. Els cultius amb fruit (per exemple, el tomàquet) tenen uns impactes ambientals més baixos que els cultius de fula (per exemple, el enciam), ja que les productivitats són més altes. No obstant això, aquestes formes d'agricultura en coberta realitzen policultiu, el disseny del qual està habitualment orientat a les hortalisses de fruit, donant lloc a una densitat de plantació més baixa de la que es pot realitzar per cultius de fulla. Un disseny millorat, que dividís el jardí segons cultiu, podria millorar i equilibrar aquestes divergències entre els tipus de cultiu.

Aquesta tesi contribueix a la comprensió del procés de desenvolupament d’una agricultura urbana i agricultura urbana en coberta competitiva i sostenible a les ciutats dels països desenvolupats mitjançant l’avenç d'aspectes metodològics i la generació de noves dades sobre el tema. Els mètodes i resultats amplien el coneixement i la comprensió de l'agricultura en coberta, l'agricultura urbana i la producció local d'aliments per tal de donar suport als processos de presa de decisions en el disseny i desenvolupament de futurs projectes d'agricultura en coberta. Futures investigacions haurien de centrar-se en l'avaluació de les percepcions dels actors socials a altres ciutats, focalitzant en aspectes específics com l'acceptació social; en quantificar el potencial de l'agricultura en coberta d’altres àrees urbanes i ciutats; i en avaluar més casos d’estudi i formes d’agricultura urbana en coberta des d'una perspectiva de sostenibilitat, fent especial èmfasi en la integració dels aspectes socials.

# Preface

The present doctoral thesis was developed within the research group on Sustainability and Environmental Prevention (Sostenipra) at the Institute of Environmental Science and Technology (ICTA) of the Universitat Autònoma de Barcelona (UAB) from October 2011 to June 2015; as well as, during the three-month research stay (September – December 2014) at the Department of Agricultural Science (DIPSA) of the *Alma Mater Studorium Università di Bologna* (UniBo), in Bologna, Italy.

This dissertation analyses the municipal compost application and production in the Mediterranean region from a sustainable perspective. This dissertation is the result of a multidisciplinary approach that aims to evaluate the implementation of urban rooftop farming systems in cities. The novelty of the dissertation relies not only on the topic but also on the integration of qualitative and quantitative tools in order to assess the social, economic and environmental aspects from a multi-actor perspective. The dissertation provides further knowledge on urban rooftop farming to support decision-making processes. Methodological proposals and specific tools are also presented.

The dissertation is mainly based on the following papers and chapters either published or under review in peer-reviewed indexed journals:

- Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, Montero JI, Rieradevall J (2013) Environmental analysis of the logistics of agricultural products from Roof Top Greenhouse (RTG) in Mediterranean urban areas. *Journal of the Science of Food and Agriculture* 93(1): 100–109. (DOI: 10.1002/jsfa.5736)
- Sanyé-Mengual E, Oliver-Solà J, Montero JI, Rieradevall J (2015) An environmental and economic life cycle assessment of Rooftop Greenhouse (RTG) implementation in Barcelona, Spain. Assessing new forms of urban agriculture from the greenhouse structure to the final product level. *International Journal of Life Cycle Assessment* (DOI: 10.1007/s11367-014-0836-9)
- Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, Montero JI, Rieradevall J (2015) Integrating horticulture into cities: A guide for assessing the implementation potential of Rooftop Greenhouses (RTGs) in industrial and logistics parks. *Journal of Urban Technology* 22(1):87-111 (DOI:10.1080/10630732.2014.942095)
- Sanyé-Mengual E, Anguelovski I, Oliver-Solà J, Montero JI, Rieradevall J (2015) Resolving differing stakeholder perceptions of urban rooftop farming in Mediterranean cities : promoting food production as a driver for innovative forms of urban agriculture. *Agriculture and Human values* (online) (DOI: 10.1007/s10460-015-9594-y)
- Sanyé-Mengual E, Martínez-Blanco J, Finkbeiner M, Cerdà M, Camargo A, Ometto AR, Velásquez LS, Villada G, Niza S, Pina A, Ferreira G, Oliver-Solà J, Montero JI, Rieradevall J. Urban horticulture in retail parks: environmental assessment of the potential implementation of Rooftop Greenhouses (RTGs) in European and South American cities. *Journal of Cleaner Production* (under review)
- Sanyé-Mengual E, Orsini F, Oliver-Solà J, Rieradevall J, Montero JI, Gianquinto G (2015) Environmental and economic assessment of multiple cultivation techniques and crops in open-air community rooftop farming in Bologna (Italy). *Agronomy for Sustainable Development* (under review)
- Sanyé-Mengual E, Oliver-Solà J, Montero JI, Rieradevall J (2015) Revisiting the environmental assessment of local food: Relevance of market data and seasonality. A case study on rooftop home-grown food in Barcelona (Spain). *International Journal of Life Cycle Assessment* (submitted)
- Sanyé-Mengual E, Oliver-Solà J, Anton A, Montero JI, Rieradevall J (2014) Environmental assessment of urban horticulture structures: Implementing Rooftop Greenhouses in

Mediterranean cities. In Schenk R, Huizenga D (eds.) Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector, San Francisco (United States) (ISBN: 978-0-9882145-7-6).

- Sanyé-Mengual E, Anguelovski I, Oliver-Solà J, Montero JI, Rieradevall J (2014) When the perception and development of Urban Rooftop Farming depend on how Urban Agriculture is defined: Examining diverging stakeholders' experiences and views in Barcelona, Spain, in Roggema R and Keeffe G (eds.) *Finding spaces for productive cities. Proceedings of the 6th AESOP Sustainable Food Planning conference*. (VHL University of Applied Sciences: Leeuwarden), pp.490-503 (ISBN 978-90-822451-2-7)
- Sanyé-Mengual E, Llorach-Masana P, Sanjuan-Delmás D, Oliver-Solà J, Josa A, Montero J, Rieradevall J (2014) The ICTA-ICP Rooftop Greenhouse Lab (RTG-Lab): closing metabolic flows (energy, water, $CO_2$) through integrated Rooftop Greenhouses. in Roggema R and Keeffe G (eds.) *Finding spaces for productive cities. Proceedings of the 6th AESOP Sustainable Food Planning conference*. (VHL University of Applied Sciences: Leeuwarden), pp.692-701 (ISBN 978-90-822451-2-7)

The following oral communications and posters presented to congresses and conferences also form part of this doctoral thesis:

- Sanyé E, Cerón I, Oliver-Solà J, Montero JI, Rieradevall J (2011) LCM of green food production in Mediterranean cities: environmental benefits associated to the distribution stage of Roof Top Greenhouse (RTG) systems. A case study of Barcelona (Spain). Poster. LCM2011. Life Cycle Management 2011: Towards Life Cycle Sustainability Management, August 2011, Berlin (Alemania).
- Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, Montero JI, Rieradevall J (2012) Periurban and innovative agrourban production areas for food self-sufficiency in the Metropolitan Area of Barcelona. Oral presentation. Agriculture in an urbanizing society, International Conference on Multifunctional Agriculture and Urban-Rural Relations, April 2012, Wageningen (The Netherlands).
- Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, Montero JI, Rieradevall J (2012) Potential and benefits of Rooftop Greenhouse (RTG) systems for agriculture production implemented in polygons of future Smart cities: a case study in Zona Franca (Barcelona). Oral presentation. Smart Cities World Congress, November 2012, Barcelona (Spain)
- Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, Montero JI, Rieradevall J (2012) Potential benefits of agrourban production systems as a sustainable strategy for food self-sufficiency in urban areas. Poster. Urban sustainability and resilience (USAR2012). 1st International Conference for Urban Sustainability and Resilience, 5-6 November 2012, London (United Kingdom).
- Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, Montero JI, Gabarrell X, Rieradevall J (2013) Ecoinnovation of Rooftop Greenhouses (RTGs) as agrourban symbiotic systems for urban areas. Poster. 7th International Conference of the International Society for Industrial Ecology (ISIE2013), 25 – 28 June 2013, Ulsan (Korea).
- Sanyé-Mengual E, Oliver-Solà J, Antón A, Montero JI, Rieradevall J (2014) Environmental assessment of urban horticulture infrastructures: Implementing Rooftop Greenhouses (RTGs) in Mediterranean cities. Oral presentation. IX International Conference on Life Cycle Assessment in the agri-food sector (LCAFOOD2014), 10-12 October 2014, San Francisco (United States).
- Sanyé-Mengual E, Oliver-Solà J, Montero JI, Gabarrell X, Rieradevall J (2014) Production and consumption comparison of conventional and local horticulture: cradle-to-farm gate and cradle-to-consumer analysis of tomato production in Almeria and Barcelona (Spain). Oral presentation. 11th ISIE Socio-Economic Metabolism section conference, 17-19 November 2014, Melbourne (Australia).

- Sanyé-Mengual E, Anguelovski I, Oliver-Solà J, Montero JI, Rieradevall J (2014) When the perception and development of Urban Rooftop Farming depend on how Urban Agriculture is defined: Examining diverging stakeholders' experiences and views in Barcelona, Spain. Oral presentation. 6th AESOP Sustainable Food Planning Conference, 5-7 November 2014, Arnhem (The Netherlands).
- Sanyé-Mengual E, Oliver-Solà J, Montero JI, Rieradevall J (2014) The ICTA-ICP rooftop greenhouse lab (RTG-Lab): closing metabolic flows through Rooftop Greenhouses in Barcelona, Spain. Oral presentation. 6th AESOP Sustainable Food Planning Conference, 5-7 November 2014, Arnhem (The Netherlands).
- Sanyé-Mengual E, Oliver-Solà J, Montero JI, Rieradevall J (2014) The ICTA-ICP rooftop greenhouse lab (RTG-Lab): closing metabolic flows through Rooftop Greenhouses in Barcelona, Spain. Poster. 6th AESOP Sustainable Food Planning Conference, 5-7 November 2014, Arnhem (The Netherlands).
- Sanyé-Mengual E, Oliver-Solà J, Montero JI, Rieradevall J (2015) How to communicate environmental impacts? Approaching LCA results to consumers for urban food products. Poster. SETAC Europe 25th Annual Meeting, 3-7 May 2015, Barcelona (Spain)
- Sanyé-Mengual E, Orsini F, Gianquinto G, Oliver-Solà J, Montero JI, Rieradevall J (2015) Integrating food production in cities for reducing the carbon footprint: accounting the environmental burdens of rooftop farming systems in Mediterranean cities. Poster. ISIE Conference 2015 - Taking Stock of Industrial Ecology, 7-10 July 2015, Surrey (United Kingdom)
- Sanyé-Mengual E, Llorach-Masana P, Sanjuan-Delmas D, Oliver-Solà J, Josa A, Montero JI, Gabarrell X, Rieradevall J (2015) The ICTA-ICP Rooftop Greenhouse Lab: coupling industrial ecology and life cycle thinking to assess innovative urban agriculture. Poster. VI International Conference on Life Cycle Assessment (CILCA 2015), 13-16 July 2015, Lima (Peru).
- Sanyé-Mengual E, Orsini F, Oliver-Solà J, Muñoz P, Gianquinto G, Rieradevall J, Montero JI (2015) Environmental performance of rooftop farming as urban food systems: outputs from case studies in the Mediterranean area. Poster. 7th International Conference on Life Cycle Management. 30August – 2 September 2015, Bordeaux (France).

Part of this doctoral thesis was developed in the framework of the FERTILECITY project "Agrourban sustainability through rooftop greenhouses. Ecoinnovation on residual flows of energy, water and $CO_2$ for food production" funded by the Spanish Ministerio de Economía y Competitividad (MINECO) (CTM2013-47067-C2-1-R). The project is coordinated by the Institute of Environmental Science and Technology (ICTA), with the participation of the Universitat Politècnica de Catalunya (UPC) and the Institute of Agriculture and Food Research and Technology (IRTA).

In addition, during the dissertation period the opportunity has been given to work in other papers, which were published in peer-reviewed journals and are also related with the goals of the dissertation:

- Cerón-Palma I, Oliver-Solà J, Sanyé-Mengual E, Montero JI & Rieradevall J (2012) Barriers and opportunities regarding the implementation of Rooftop Greenhouses (RTEG) in Mediterranean cities of Europe. *Journal of Urban Technology* 19 (4): 87-103.
- Cerón-Palma I, Sanyé-Mengual E, Oliver-Solà J, Montero JI & Rieradevall J (2013) Towards a green sustainable strategy for social neighbourhoods in Latin America: Case from social housing in Merida, Yucatan, Mexico. *Habitat International* 38: 47-56.

Furthermore, the participation in other projects and publications of the Sostenipra research group provided further knowledge on the application of industrial ecology and sustainability assessment tools.

*Projects:*

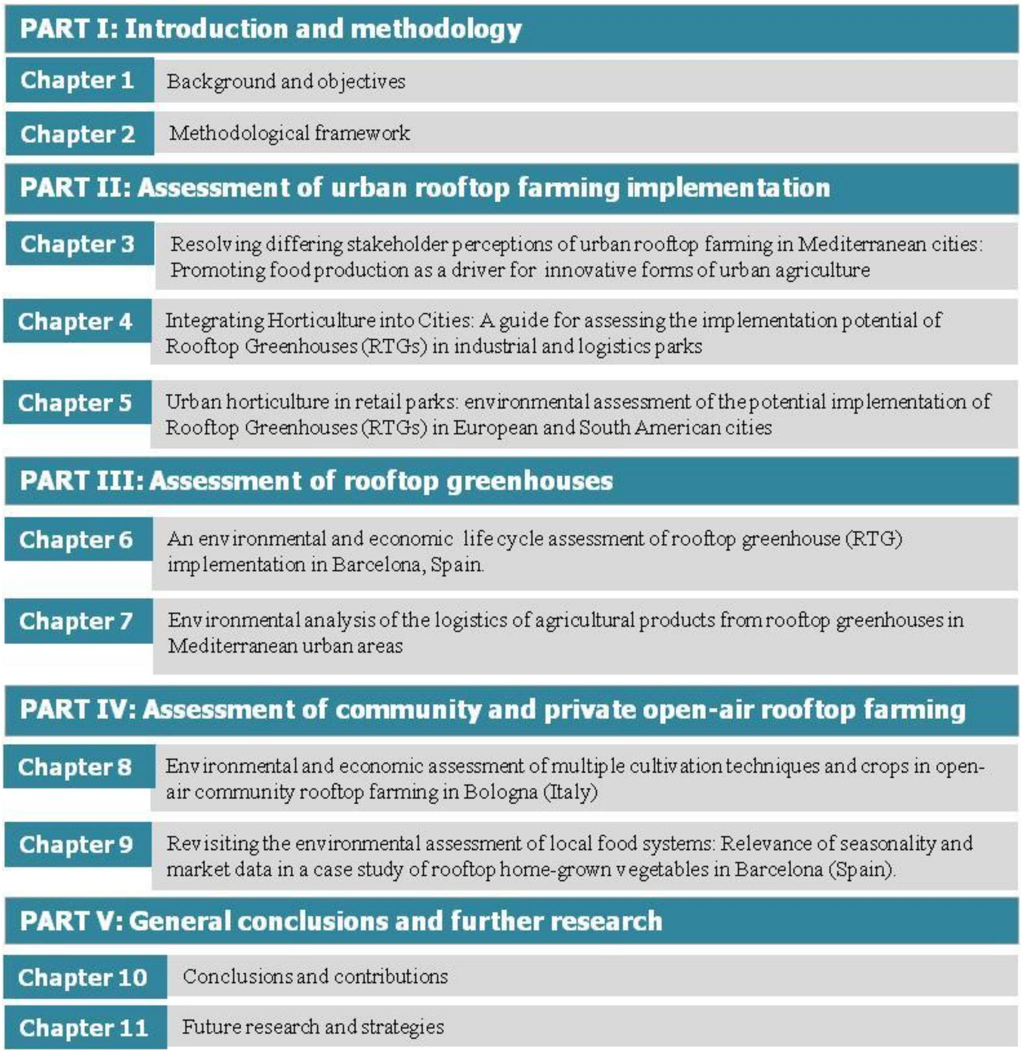
- SMART PARKS: Ecoinnovation in Smart Parks - Analysis of methods and sustainable strategies to promote symbioses between industrial, urban and agrarian systems in Brazil and Spain (HBP-2012-0216). Funded by MECD – Spanish Ministry of Education, Culture and Sports.
- Proyecto piloto sobre ecodiseño (2ª fase) para el desarrollo de 3 ecoproductos en otras tantas empresas españolas innovadoras. Funded by ENISA – National company for innovation.
- Proyecto M-ECO, Investigación para la mejora de la sostenibilidad del sector de la madera y mueble en Andalucía a través de la Eco-innovación. Funded by Junta de Andalucía.

*Publications:*

- Sanyé-Mengual E, Pérez-López P, González-García S, Garcia Lozano R, Feijoo G, Moreira MT, Gabarrell X, Rieradevall J (2014) Eco-Designing the Use Phase of Products in Sustainable Manufacturing. The Importance of Maintenance and Communication-to-User Strategies. *Journal of industrial ecology* 18(4):545-557
- Sanyé-Mengual E, Romanos H, Molina C, Oliver MA, Ruiz N, Pérez M, Carreras D, Boada M, Garcia-Orellana J, Duch J, Rieradevall J (2014) Environmental and self-sufficiency assessment of the energy metabolism of tourist hubs on Mediterranean islands: the case of Menorca (Spain). *Energy Policy* 65: 377–387.
- Sanyé E, Oliver-Solà J, Gasol CM, Farreny R, Gabarrell X, Rieradevall J (2012). Life Cycle Assessment of energy flow and packaging use in food purchasing. *Journal of Cleaner Production, 25: 51 -59.*
- Mendoza JM, Sanyé-Mengual E, Angrill A, García-Lozano R, Feijoo G, Josa A, Gabarrell X, and Rieradevall J (2015) Development of urban solar infrastructure to support low-carbon mobility. *Energy policy* (Accepted, May 2015)
- Gasol CM, Sanyé E, Sevigné E, Martínez J, Font X, Artola A, Sánchez A, Anton A, Muñoz P, Montero JI, Rieradevall J & Gabarrell X (2012). *Database Availability. Life Cycle Assessment Database of the Sudoe Area*, in: Joaquim Comas & Sadurní Morera (eds.) Life Cycle Assessment and Water Management – related issues (ISBN 978-84-9984-163-2)
- Sanyé-Mengual E, Garcia Lozano R, Farreny R, Oliver-Solà J, Gasol CM & Rieradevall J (2014) *Introduction to the Eco-Design Methodology and the Role of Product Carbon Footprint*. In: Muthu, S.S. (ed) Assessment of Carbon Footprint in Different Industrial Sectors. Vol. 1. Singapore: Springer Singapore.
- Sanyé-Mengual E, Garcia Lozano R, Oliver-Solà J, Gasol CM & Rieradevall J (2014) *Eco-design and product carbon footprint use in the packaging sector.* In: Muthu, S.S. (ed) Assessment of Carbon Footprint in Different Industrial Sectors. Vol. 1. Singapore: Springer Singapore.

# Structure of the dissertation

This thesis is organised into five main parts and eleven chapters, as follows:



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|---|---|
| **PART I: Introduction and methodology** | |
| **Chapter 1** | Background and objectives |
| **Chapter 2** | Methodological framework |
| **PART II: Assessment of urban rooftop farming implementation** | |
| **Chapter 3** | Resolving differing stakeholder perceptions of urban rooftop farming in Mediterranean cities: Promoting food production as a driver for innovative forms of urban agriculture |
| **Chapter 4** | Integrating Horticulture into Cities: A guide for assessing the implementation potential of Rooftop Greenhouses (RTGs) in industrial and logistics parks |
| **Chapter 5** | Urban horticulture in retail parks: environmental assessment of the potential implementation of Rooftop Greenhouses (RTGs) in European and South American cities |
| **PART III: Assessment of rooftop greenhouses** | |
| **Chapter 6** | An environmental and economic life cycle assessment of rooftop greenhouse (RTG) implementation in Barcelona, Spain. |
| **Chapter 7** | Environmental analysis of the logistics of agricultural products from rooftop greenhouses in Mediterranean urban areas |
| **PART IV: Assessment of community and private open-air rooftop farming** | |
| **Chapter 8** | Environmental and economic assessment of multiple cultivation techniques and crops in open-air community rooftop farming in Bologna (Italy) |
| **Chapter 9** | Revisiting the environmental assessment of local food systems: Relevance of seasonality and market data in a case study of rooftop home-grown vegetables in Barcelona (Spain). |
| **PART V: General conclusions and further research** | |
| **Chapter 10** | Conclusions and contributions |
| **Chapter 11** | Future research and strategies |

## Part I. Introduction, objectives and methodology

**Part I** is composed of two chapters. **Chapter 1** *[Background and objectives]* introduces the background of urban rooftop farming, focusing on: the global and urban food issues that have led to the development of a local food sector; the concepts, types, functions and development of urban agriculture; the definition of the concepts and types, current projects and practices, and the specific opportunities and challenges of urban rooftop farming; and the motivations and objectives of this dissertation. **Chapter 2** *[Methodological framework]* details the methodological framework of this dissertation by defining the methods and tools employed and describing the main characteristics of the case studies.

## Part II. Assessment of urban rooftop farming implementation

**Part II** is composed of three chapters. **Chapter 3** [*Resolving differing stakeholder perceptions of urban rooftop farming in Mediterranean cities: Promoting food production as a driver for innovative forms of urban agriculture*] deepens in the perceptions of stakeholders related to urban agriculture and rooftop farming in the city of Barcelona by performing qualitative interviews. The study unravels the challenges, barriers and benefits of the potential implementation of urban rooftop farming. **Chapter 4** [*Integrating Horticulture into Cities: A guide for assessing the implementation potential of Rooftop Greenhouses (RTGs) in industrial and logistics parks*] develops a tool that combines geographic information systems (GIS) and life cycle assessment (LCA) to quantify and evaluate the implementation of commercial rooftop greenhouses (RTGs) in industrial and logistics parks. The tool is applied to the case study of Zona Franca in Barcelona (Spain). **Chapter 5** [*Urban horticulture in retail parks: environmental assessment of the potential implementation of Rooftop Greenhouses (RTGs) in European and South American cities*] uses the GIS-LCA tool to anlyse the potential implementation of RTGs in retail parks in different world regions. The assessment focuses on the potential benefits of integrated RTGs (i-RTGs) in the different climatic areas and the identification of the constraints and challenges of such systems.

## Part III. Assessment of rooftop greenhouses

**Part III** includes two chapters on rooftop greenhouses. **Chapter 6** [*An environmental and economic life cycle assessment of rooftop greenhouse (RTG) implementation in Barcelona, Spain.*] accounts for the environmental impacts and economic cost of a pilot experience: the rooftop greenhouse Lab (RTG-Lab) in Bellaterra (Spain). The assessment is performed at three levels: greenhouse structure, cradle-to-farm gate, and cradle-to-consumer. The local system is compared with the conventional production in multitunnel greenhouses in Almeria. **Chapter 7** [*Environmental analysis of the logistics of agricultural products from rooftop greenhouses in Mediterranean urban areas*] focuses on the supply-chain of conventional and local food products. The assessment details the supply-chain of tomatoes from Almeria to Barcelona and the potential local supply-chain of tomatoes from RTGs in Barcelona.

## Part IV. Assessment of community and private open-air rooftop farming

**Part IV** assesses open-air forms of rooftop farming. **Chapter 8** [*Environmental and economic assessment of multiple cultivation techniques and crops in open-air community rooftop farming in Bologna (Italy)*] quantifies the environmental burdens and the economic costs of fruit and vegetables crops in a community rooftop garden in Bologna (Italy). Particular attention is paid to the analysis of different cultivation techniques and crops in order to provide recommendations for the design of future rooftop gardens. **Chapter 9** [*Revisiting the environmental assessment of local food systems: Relevance of seasonality and market data in a case study of rooftop home-grown vegetables in Barcelona (Spain)*] analyses the environmental impacts of a private rooftop garden in the city of Barcelona. This chapter focuses on the development of the life cycle methodology for assessing urban food systems from a local production perspective by integrating market data and seasonality in the analysis.

## Part V. General conclusions and future research

**Part V** includes **Chapter 11** [*Conclusions and contributions*] and **Chapter 12** [*Future research and strategies*] and provides the general conclusions of the dissertation and proposes future fields of research associated with urban rooftop farming, urban agriculture and local food systems.

[*Note:* Each chapter from 3 to 9 presents an article–either published or under review. For this reason, an abstract and a list of keywords are presented at the beginning of the chapter, followed by the main body of the article].

# Part I

## Introduction, objectives and methodology

# Chapter 1

# Introduction and objectives

Picture: *Emplacement of a future rooftop greenhouse (Paris, France)*
*(©Esther Sanyé-Mengual)*

# Chapter 1

This chapter introduces the background of urban rooftop farming. First, the global and urban food issues that have led to the development of a local food sector are described. Second, an introduction to urban agriculture is performed by dealing with the concepts, types, functions and development. Third, the core of this dissertation, urban rooftop farming, is presented by defining the concepts and types, showing current projects and practices and identifying the specific opportunities and challenges of these systems. Finally, the last sections outline the motivations and objectives of this dissertation.

## 1.1. The food and the city: increased demand, increased awareness

World population is expected to surpass the value of 9.500 million of inhabitants by 2050 (United Nations 2012). Particular attention is paid to urban areas, where population is getting concentrated. Since 2007, urban areas represent more than half of the population and this trend is forecasted to grow up to almost 70% by 2050 (United Nations 2014). Urban population is particularly important in developed countries, where it represents around 80% of the population, and in emerging areas, where megacities are expanding (e.g., Asia) (United Nations 2014) (see Figure 1.1).

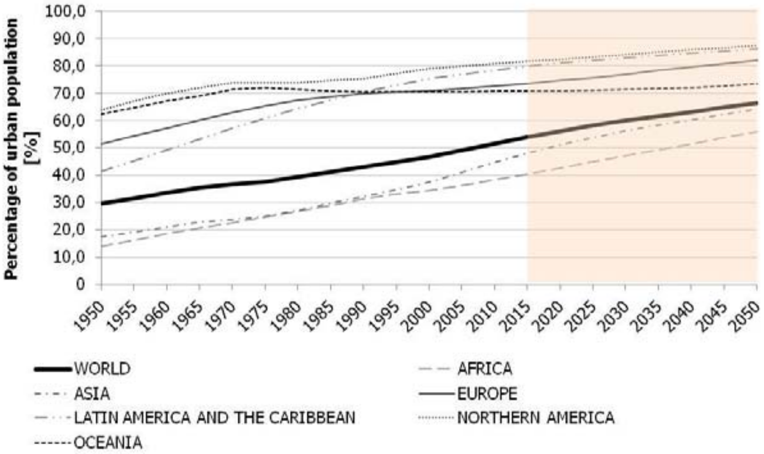

***Figure 1.1.*** *Evolution and prevision of the percentage of urban population (%) in the world and main regions (1950-2050).*

*Source: Own elaboration from United Nations (2014).*

This fact puts more pressure on the global food security issue, since a growing population results in an increasing food demand. The United Nations Food and Agriculture Organisation (FAO) coined the term "food security" in 1945 as 'a situation that exists when all people, at all times have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life' with the aim of highlighting the disparities of food access between world regions (Burton et al. 2013).

At the global scale, satisfying the food demand will face several challenges. First, agricultural production is required to become more sustainable and more intensive to boost crop yields without enlarging crop areas. However, multiple factors put against the wall the availability and functionality of fertile soil. Second, urbanization exerts a direct occupation of fertile areas, which are usually displaced to less suitable places. Third, past agricultural practices have led to agronomic constraints, such as a reduction in nutrient availability and environmental risks (e.g., chemical contamination). Finally, climate change has made crops more vulnerable by increasing the recurrence and effects of negative phenomena, such as droughts, and by expanding the areas affected by desertification and water scarcity (Godfray et al. 2010; Pelletier and Tyedmers 2010; Foley 2011; FAO 2013a).

At the city scale, the increase of population implies an expansion of the urbanized area, causing two main issues: the destruction of farmland and the disconnection of consumption and production areas (Seto et al. 2011; Paül and McKenzie 2013). The urban sprawl not only occupies and displaces farmland area but also increases the land value, leading to an abandonment of some farming activities as land speculation becomes more profitable (Robinson 2004). Consequently, the importance of farmland and its potential food supply of periurban areas are notably reduced (Figure 1.2) (Allen 2003; Zeng et al. 2005; Thapa and Murayama 2008; Zasada 2011; Paül and McKenzie 2013). However, an increased population demands a larger amount of food and, thus, the rift between production and consumption areas is enlarged, enlarging the *food miles* of products which need to be imported to meet the urban food demand (Figure 1.2).

***Figure 1.2.*** *Food implications of urban expansion.*

In this context, the design of sustainable cities is in the global agenda, such as the “Thematic Strategy on the Urban Environment” proposed by the European Commission (European Commission 2005). Cities are open systems that rely on external resources, leading to an important contribution to global environmental impacts (Girardet 2010). Although occupying only 2% of Earth’s surface, the environmental burdens of urban activity extend beyond city borders. Notwithstanding that cities generate 75% of the global economic output, they are responsible for 75% of carbon emissions and consume up to 80% of the global energy and material supply (UN-Habitat 2011a; UN-Habitat 2011b; UNEP 2013). Regarding food, sustainable cities may enhance the local production and consumption of food products thereby reducing the *food miles* of citizen diets (UNEP 2011a; UNEP 2013; UN-Habitat 2013a).

Particularly in developed countries, beyond policy recommendations to improve urban sustainability, the environmental awareness of citizens and the development of alternative food supply-chains have boost a renewed local food sector (Weatherell et al. 2003). The development of regional and local food systems have approached the relationships between producers and consumers while shortening the food supply-chains (Hinrichs 2000; Marsden et al. 2000; Steel 2008). Farmers’ markets, community-supported agriculture (CSA) schemes or on-site retailing have contributed to supply the growing demand of local food products, which are largely accepted by consumers, who perceived local products as a higher quality, fresher, more nutritive and more traceable option (Lee 2001; La Trobe 2001; Boyle 2003; Seyfang 2004). Furthermore, consumers identify local food systems as a sustainable alternative from a socio-economic perspective since they support the local economies and, thus, the local society (Chambers et al. 2007). However, urban agriculture is expected to address certain needs and supply the demand for local food while complementing the conventional market of fresh produce, rather than providing cities with all the fresh produce requirements and substituting the industrial agriculture market, due to land constraints among others (Badami and Ramankutty 2015).

The expansion of the local food market counteracts the effects of urbanization by two main processes (Figure 1.3). First, the increased demand of local food revitalizes the farmland close to cities, where farmers can develop feasible businesses by using short-supply schemes. Furthermore, customers value the locality of products and accept premium prices for local food (Feldmann and Hamm 2015), giving higher margins to farmers and making periurban areas attractive for new businesses. Second, the local food movement encompasses also the boosting of periurban and urban agricultural (PUA) activities which provide citizens with fresh produce by occupying empty spaces in urban areas, such as vacant lots or rooftops (Cohen et al. 2012; Grewal and Grewal 2012).

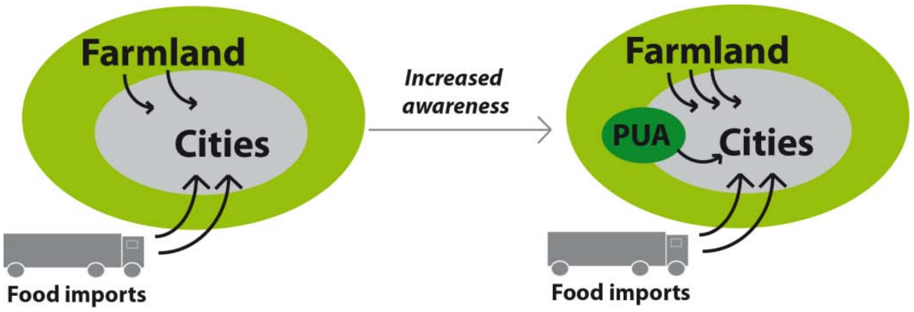

***Figure 1.3.*** *Revitalization of local production.*

## 1.2. Urban agriculture: a matter of food security, environmentalism and social needs

Within the local food movement, urban agriculture experiences have spread over cities in the last years with the aim of increasing the urban area devoted to food production thereby contributing to urban food security and resilience (Mok et al. 2013; Ackerman et al. 2014; Tornaghi 2014; Orsini et al. 2014; Specht et al. 2015). This section introduces the concepts, nomenclature and development of urban agriculture, as well as the multifunctionality of such experiences.

### *1.2.1. Concepts and nomenclature of urban agriculture (UA)*

There are multiple definitions of “Urban agriculture” (UA) that have been used in the literature and in policy-making. Main differences among them are linked to spatial, production, function and market specifications. Definitions range from generic and global, such as the FAO conceptualization, to recent and specific, such as in the Five Borough Farm project. Common and recent definitions of UA are collected in Table 1.1. The specific aspects of the spatial, production, function and market dimensions of each are shown in Table 1.2.

***Table 1.1.*** *Common and recent definitions of urban agriculture.*

| **Source** | **Definition** |
|---|---|
| *FAO* | **Urban and peri-urban** agriculture (UPA) can be defined as the **growing of plants and the raising of animals** within and around cities |
| *RUAF foundation* | Urban agriculture can be defined shortly as the **growing of plants and the raising of animals within and around cities**. The most striking feature of urban agriculture, which distinguishes it from rural agriculture, is that it is integrated into the urban economic and ecological system: urban agriculture is embedded in -and interacting with- the urban ecosystem. Such linkages include the use of urban residents as labourers, use of typical **urban resources** (like organic waste as compost and urban wastewater for irrigation), direct **links with urban consumers**, direct impacts on urban ecology (positive and negative), being part of the urban food system, competing for land with other urban functions, being influenced by urban policies and plans, etc. |
| *US EPA* | **City and suburban** agriculture takes the form of backyard, roof-top and balcony gardening, community gardening in vacant lots and parks, roadside urban fringe **agriculture and livestock** grazing in open space. Urban agriculture is an important source of **environmental and production efficiency benefits**. The use of best management practices (BMPs) and integrated farming systems protect soil fertility and stability, prevent excessive runoff, provide habitats for a widened diversity of flora and fauna, reduce the emissions of $CO_2$, increase carbon sequestration, and reduce the incidence and severity of natural disasters such as floods and landslides |
| *Five Borough Farm project* | Urban agriculture can be defined as growing **fruits, herbs, and vegetables and raising animals in cities**, a process that is accompanied by many other complementary activities such as processing and distributing food, collecting and reusing food waste and **rainwater**, and **educating**, organizing, and employing local residents. Urban agriculture is integrated in individual urban communities and neighborhoods, as well as in the ways that cities function and are managed, including municipal policies, plans, and budgets |
| *Mougeot 2000, based on Smit et al. 1996* | UA is an industry located **within (intraurban) or on the fringe (periurban)** of a town, a city or a metropolis, which grows or raises, processes and distributes a diversity of **food and non-food products**, (re-)using largely human and material resources, products and services found in and around that urban area, and in turn supplying human and material resources, products and services largely **to that urban area** |
| *Mok et al. 2013* | **Horticultural activities within an urban or peri-urban** setting, rather than animal husbandry, aquaculture, or arboriculture, since food plant cultivation is the dominant form of urban agriculture |

***Table 1.2.*** *Specifications of common urban agriculture definitions.*

| **Source** | **Spatial** | | **Production** | | | | **Function** | | | | | | | | | | **Market** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Within cities** | **Around cities** | **Plant growing** | **Animal husbandry** | **Agroforestry** | **Non-food products** | **Multifunctional** | **Soil protection** | **Water protection** | **Climate protection** | **Resource efficient** | **Biodiversity** | **Social inclusion** | **Health** | **Education** | **Leisure** | **Local oriented** |
| *FAO* | ● | ● | ● | ● | ● | ● | ● | | | | | | | | | | |
| *RUAF foundation* | ● | ● | ● | ● | | | | | ● | | ● | | | | | | ● |
| *US EPA* | ● | ● | ● | | | | ● | ● | ● | ● | ● | ● | | ● | | ● | |
| *Five Borough Farm project* | ● | | ● | | | | | | ● | | ● | | ● | | ● | | ● |
| *Mougeot 2000, based on Smit et al. 1996* | ● | ● | ● | ● | ● | ● | | | | | | | | | | | |
| *Mok et al. 2013* | ● | ● | ● | | | | | | | | | | | | | | |

The definition of UA depends on the framework were it was conceptualized. There are global definitions that also encompass UA in developing countries, such as by the inclusion of non-food products (e.g., fuel). Other definitions were framed in a specific context. The Five Borough Farm project was developed in the city of New York and the definition only refers to agriculture within the city, while excluding the periurban areas. Some definitions emphasize the role of urban agriculture as a local food system, while others pinpoint the multifunctionality of such activities by identifying further benefits (such as education).

Among this variety and , this dissertation focuses on urban agriculture in developed countries, which is often referred to as Global North, and uses the following definition, which summarizes the discussion around UA conceptualizations of the Working group 1 of the COST Action "Urban Agriculture Europe" (Lohrberg and Timpe 2012) (identified in orange in Figure 1.4):

**Definition of urban agriculture used in this dissertation**

Urban agriculture are farming operations taking place in and around the city that beyond food production provides environmental services (soil, water and climate protection; resource efficiency; biodiversity), social services (social inclusion, education, health, leisure, cultural heritage) and supports local economies by a significant direct urban market orientation.

Thus, there are some difficulties to reach a global definition of urban agriculture. The lack of a common definition of UA among stakeholders and organizations becomes a gap that needs to be covered prior to the development of urban agriculture planning and policy. The variety of definitions is partly based on the diversified nomenclature of UA. Thus, the multiple natures and types of UA have led to a proliferation of ways to name these experiences. Figure 1.4 illustrates the confusing cloud of concepts and specifications when defining and naming urban agriculture, in terms of type of property, production, management and objective. This issue is core in the Chapter 3 of this dissertation.

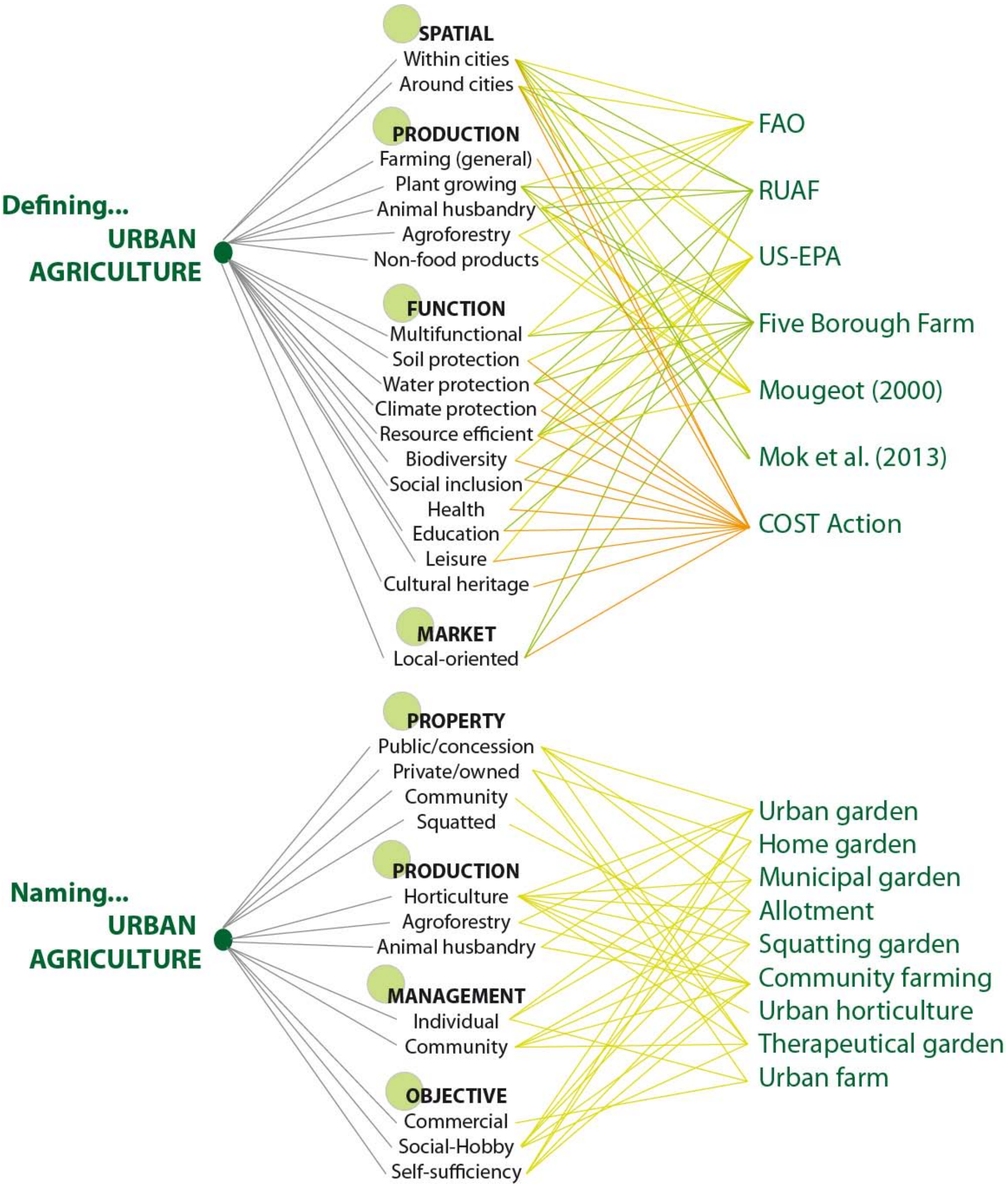

***Figure 1.4.*** *Concepts use in the definitions and nomenclature of urban agriculture.*

### *1.2.2. The multifunctional urban agriculture*

Urban agriculture is characterized by being multifunctional. Main functions are enhancing food security, providing environmentally-friendly food, educating and promoting health habits, and building and empowering communities (e.g., Altieri et al. 1999; Lee 2001; Saldivar-tanaka and Krasny 2004; Kortright and Wakefield 2010; Bendt et al. 2013; Hu et al. 2013; Orsini et al. 2014). Although projects can focus on a single function, UA activities tend to provide many secondary ones. For example, a school garden aims to provide education on food and environment. However, school gardens also improve the health habits of children and source the school kitchen with local and ecologic food (Morris 2002; Morgan et al. 2010). The different functions of UA can be explained throughout the development of urban agriculture along the last century (Figure 1.5).

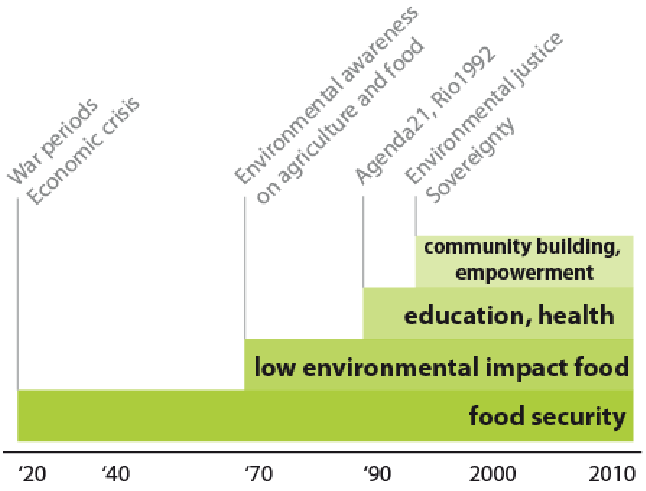

***Figure 1.5.*** *UA functions along UA development.*

## (a) Food security

During the war periods and Great Depression ('30), urban agriculture was essential for guaranteeing the food security of the United States and Europe. In this period, the administration promoted the development of urban gardens in both public and private spaces, where citizens could cultivate vegetables for feeding the population. They were the *War gardens* (WWI), *Relief Gardens* (Great Depression) and *Victory gardens* (WWII) (Bassett 1981; McClintock 2010; Mok et al. 2013). A matter of food security was also the increase of urban agriculture in Cuba to access fresh food during the collapse of the socialist bloc between 1989 and 1993 (the Special Period) (Altieri et al. 1999; Cruz and Medina 2003).

Recently, urban agriculture has been partly revitalized due to food security. The financial crisis of 2008 caused a rapid rise of food and commodity prices, which resulted in a higher number of citizens that were unemployed, facing financial and food insecurity issues which were improved by their engagement in UA activities (Carney 2011; Taylor and Taylor Lovell 2012). Beyond the global economy context, the creation of low-income neighbourhoods in cities has also led to the origin of "food deserts": urban areas with a limited access to affordable fresh food, where urban gardens play a key role in coping community food insecurity (Guy et al. 2004; Wrigley et al. 2004; Smoyer-tomic et al. 2006; Beaulac et al. 2009; Alkon and Agyeman 2011; McClintock 2011; Carney 2011; Block et al. 2011; Tornaghi 2014). Furthermore, urban agriculture also contributes to the urban food resilience after disasters, such as extreme climatic events which are progressively becoming more regular.

## (b) Low environmental impact food

In 1962 "Silent spring" of Rachel Carson (1962)warned about the environmental risks of the modern agricultural industry and the use of chemicals, increasing the environmental awareness of food and agriculture. As a result, citizens initiated backyards and urban gardens which became a source of chemical-free food that was also an alternative to the conventional food industry (Bassett 1981; Howe and Wheeler 1999; Mok et al. 2013). During this period, urban farms and community gardens expand in number (Howe and Wheeler 1999) by offering not only environmentally-friendly but also healthy products.

Environmental concerns have been since then a motivation to engage in urban agriculture experiences. Currently, UA is dominated by organic practices that close organic waste flows and preserves biodiversity (Howe and Wheeler 1999; Kortright and Wakefield 2010; Lin et al. 2015). Furthermore, the traceability of products is still a motivation behind urban gardens, which aim to guarantee the consumption of chemical-free food (Kortright and Wakefield 2010; Calvet-Mir et al. 2012a).

### (c) Education and health

The Agenda 21 defined in the United Nations Conference on Environment & Development in Rio de Janerio (known as Rio 92) included the promotion of environmental education, public awareness and training. During the implementation process of Agenda 21, gardens have gained popularity in education entities. School gardens have become a common tool to approach children to nature, life sciences and health (Bell 2001; Coffey 2001). Furthermore, education opportunities are an added-value of home gardens (Kortright and Wakefield 2010). Currently, urban farms and projects offer education programs and training (Cohen et al. 2012).

The participation in UA experiences improves the health of citizens. School gardens can improves children health by enhancing positive changes in diet habits (Morris 2002; Morgan et al. 2010). Community gardens play also a key role on health and several studies linked the participation in community gardens to an improved wellbeing (Wakefield et al. 2007; Alaimo et al. 2008; D'Abundo and Carden 2008; Kingsley et al. 2009; Wilkins et al. 2015). Furthermore, healing properties at the individual level have been related to gardens, which can help participants in the recovering process from traumatic experiences (Marcus and Barnes 1999; Gerlach-Spriggs et al. 2004).

### (d) Community building and empowerment

Urban agriculture has notable effects at the community scale by supporting community building and empowerment processes. Even more, addressing social issues has been sometimes the main goal of UA projects. Community-led UA projects become a place of encounter between neighbours that boost social inclusion, self-organization and cohesion, which commonly lead to a community empowerment (Howe and Wheeler 1999; Armstrong 2000; Lyson 2004; Lawson 2005; Teig et al. 2009; Carney 2011; Block et al. 2011; Guitart et al. 2012).

Some community UA initiatives have focused towards food sovereignty as a form of empowerment (Carney 2011; Kirwan and Maye 2012). Via Campesina (2002) defined food sovereignty as the community's right to define its own food and agricultural systems. In this context, UA projects are a way of re-commoning the urban land for food production (Tornaghi 2014), while creating an alternative food supply way to the global industrial food system (Wekerle 2004; DuPuis et al. 2011; Block et al. 2011).

## 1.3. Urban rooftop farming: making buildings fertile

Urban rooftop farming (URF) is the focus of this dissertation. URF play a key role as a form of building-based urban agriculture that is growing in popularity within the local food systems (Figure 1.6). This section describes the concepts and definitions linked to urban rooftop farming, the current practices and typologies and main opportunities and challenges of these systems.

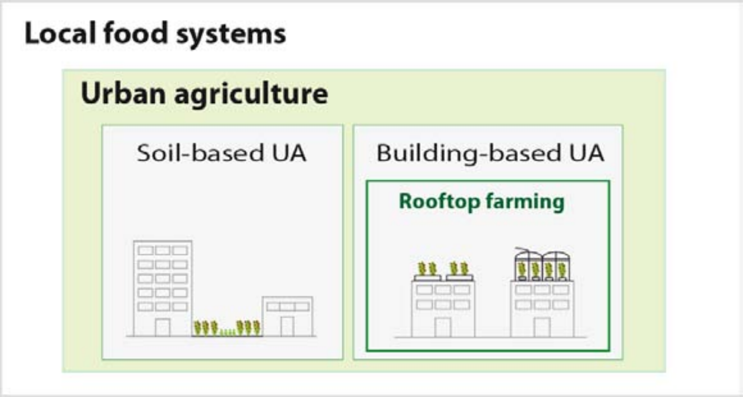

***Figure 1.6.*** *Role of urban rooftop farming within urban agriculture and local food systems.*

### *1.3.1. Concepts and definitions of urban rooftop farming (URF)*

Urban rooftop farming (URF) is part of the building-based urban agriculture that has recently occupied built infrastructures. Within the literature, building-based UA has been conceptualized as Vertical farming, Building-Integrated Agriculture (BIA) or Zero-Acreage farming (ZFarming).

Traditionally, building-based UA has been identified with the term Vertical Farming, which was defined by Dickson Despommier as:

> *Farming inside tall buildings within the cityscape* (Despommier 2008; Despommier 2009; Despommier 2010; Despommier 2011).

Also, Ted Caplow (Caplow 2009) coined the term *Building-Integrated Agriculture (BIA)* as:

> *A new approach to production based on the idea of locating high-performance hydroponic farming systems on and in buildings that use renewable, local sources of energy and water.*

However, both concepts were based on a high-tech perspective of building-based UA and current building-based practices were excluded from these definitions.

Recently, Specht et al. (2014) introduced the term Zero-acreage farming (ZFarming) which included:

> *All types of urban agriculture characterized by the non-use of farmland or open space, thereby differentiating building-related forms of urban agriculture from those in parks, gardens, urban wastelands, and so on.*

Therefore, this definition encompassed from vertical greenhouses or indoor farms to rooftop gardens, rooftop greenhouse or edible walls, regardless the type of technology used.

Figure 1.7 displays the different concepts and forms of building-based UA. Zfarming and BIA would be the more general concepts. Skyfarming (Germer et al. 2011) and Vertical farming refer exclusively to vertical farms which are commonly new buildings entirely devoted to food production. Within existing buildings, current practices are edible walls, indoor farming (i.e., which usually employs artificial lighting such as LED) and rooftop farming.

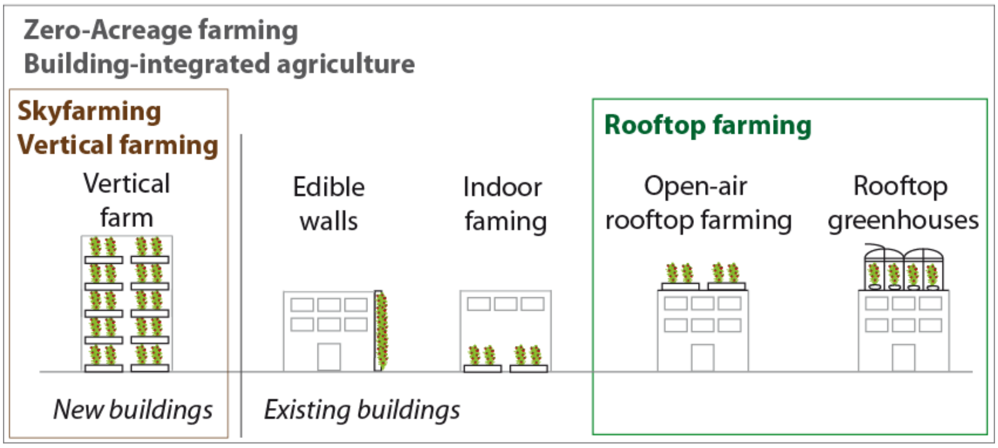

***Figure 1.7.*** *Typologies and nomenclatures for urban agriculture on buildings and rooftop farming.*

This dissertation focuses on urban rooftop farming (URF), defined as follows:

**Definition of urban rooftop farming used in this dissertation**

Urban rooftop farming is the development of farming activities on the top of buildings by taking advantage of the available spaces in roofs or terraces. URF can be developed through open-air and protected technologies and used for multiple purposes.

### *1.3.2. Urban rooftop farming typologies*

Urban rooftop farming typologies can be defined based on multiple factors, such as urban agriculture (Figures 1.4 and 1.5). To simplify the understanding of the main typologies of URF, these were defined based on two main variables: type of farming and objective.

- Type of farming differentiates between protected and open-air practices, rather than detailing the type of cultivation or technology employed. Thus, URF can be classified in protected rooftop farming (i.e., rooftop greenhouses) or open-air rooftop farming.
- Objective is also a dichotomy category. URF are globally divided into commercial (i.e., for-profit) and social activities. Social URF can though range from private rooftop farming in terraces to rooftop gardens addressing social inclusion in low-income neighbourhoods.

Then, four main URF typologies are established (Figure 1.8):

- Commercial rooftop greenhouses, such as Lufa Farms in Montreal.
- Socially-oriented rooftop greenhouses, such as the educative RTG of the Manhattan school for children in New York.
- Rooftop farms, such as Brooklyn Grange in New York.
- Socially-oriented rooftop gardens, which encompass from community rooftop gardens in residential buildings (e.g., Via Gandusio in Bologna) to therapeutic rooftop gardens in hospitals (e.g., Wiegmann-Klinik in Berlin).

***Figure 1.8.*** *Urban rooftop farming typologies.*

### *1.3.3. Current practices*

Urban rooftop farming has sprout over cities in developed countries mainly in the form of rooftop farms and rooftop greenhouses (Thomaier et al. 2015). Dominated by commercial initiatives, urban rooftop farming provide local food which is mostly environmentally-friendly (e.g., chemical-free, organic practices) and devoted to the community (e.g., CSA, local retailers). This section compiles some examples of rooftop farms and greenhouses.

#### (i) Cultivation techniques

Different cultivation techniques are used in rooftop farming, which are in this dissertation classified as follows:

- soil production, refers to the use of soil as growing media for vegetables production.
- soil-less production, refers to the use of alternative substrates to soil as growing media for vegetables production (e.g., perlite, coconut fiber).
- hydroponic production, refers to the use of water as the growing media for vegetables production (e.g., Nutrient Film Technique, NFT).

#### (ii) Open-air rooftop farming

Rooftop farms and gardens are the most common type of URF project (Thomaier et al. 2015). Numerous rooftop farms have been developed in the recent years, mostly in North America, where urban agriculture has notably raised. Rooftop farms are commonly experiences that use soil production and promote organic farming (i.e., compost), as well as sell added-value products (e.g., marmalade). The projects commonly provide further benefits to the community, such as offering education programmes. Due to its novelty, some farms also rent their space for the organization of events (e.g., Brooklyn Grange).

The Brooklyn Grange[1] is one of the most known rooftop farms in New York (United States). Founded in 2010, the company already has two rooftop farms and a bee apiary on multiple rooftops in New York. Beyond food production, Brooklyn grange participates in youth education programs through the association *City Growers*[2] as well as has a training program on urban agriculture and beekeeping.

- Brooklyn Grange

| | | |
|---|---|---|
| **Type** | Commercial rooftop greenhouse |  Flagship farm ©Brooklyn Grange<br> Navy Yard Farm ©Brooklyn Grange |
| **Name** | Brooklyn Grange | |
| **Location** | Long Island and Brooklyn, NY, United States | |
| **Area** | 4,000 m$^2$ - 6,000 m$^2$ | |
| **Year** | 2010 – 2012 | |
| **Building type** | Business building<br>(Flaghsip)<br>Navy yard building | |
| **Supply-chain** | CSA<br>Retailers<br>Wholesale | |
| **Produce** | Vegetables, honey, sauces | |
| **Management** | Soil production following organic practices | |

The project Hell's kitchen farm[3] is an urban rooftop farm installed in the Hell's Kitchen neighbourhood, known this way due to the scarcity of affordable fresh produce. Managed and run by volunteers, the farm addresses the nutritional security by providing local and healthy food to the community through a Community Supported Agriculture (CSA) program.

- Hell's Kitchen rooftop farm

| | | |
|---|---|---|
| **Type** | Rooftop farm |  ©Hell's Kitchen |
| **Name** | Hell's Kitchen | |
| **Location** | New York, United States | |
| **Area** | 380 m$^2$ | |
| **Year** | 2010 | |
| **Building type** | Church | |
| **Supply-chain** | CSA | |
| **Produce** | Basil, Beans, Blueberries, Cabbage, Collard Greens, Chives, Cucumbers, Eggplant, Garlic, Kale, Lettuce, Oregano, Peas, Peppers, Potatoes, Radishes, Rosemary, Scallions, Tomatoes | |
| **Management** | Soil production in raised beds, use of self-made compost | |

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[1] http://brooklyngrangefarm.com/

[2] https://citygrowers.org/

[3] http://www.hkfp.org/

Other consolidated rooftop farms are the Eagle Street Rooftop farm[4] (Brooklyn, New York), the Higher Ground Farm[5] (Boston, New York) and the HK Farm[6] (Singapore). There are other examples of rooftop gardens that are focused on addressing certain social or environmental issues. Cloud 9[7] is a non-profit organization that has recently launched a demonstrative rooftop garden in Philadelphia (New York) to increase the citizens' awareness of the environmental and social benefits of rooftop farming. Cloud 9 also provides education and workshops on the topic (Figure 1.9).

***Figure 1.9.*** *Rooftop garden of Cloud 9 (Philadelphia, USA).*

*Source: ©Cloud 9.*

### (iii) Rooftop greenhouses

Rooftop greenhouses are mostly commercial projects located in North America. These type of experiences use high-technology practices, such as hydroponics and controlled-environment, in order to maximize the crop yield while minimizing the costs and the environmental burdens of the activity. In Canada, Lufa Farms[8] constructed the first commercial-scale rooftop greenhouse in 2010. The pilot greenhouse was the *Ahuntsic* which combined different cultivation techniques in a polyculture greenhouse with differentiated thermal areas. In the United States, Gotham Greens[9] also runs a rooftop greenhouse built up to a former warehouse in New York. Both companies have expanded their businesses by constructing new rooftop greenhouses. Also in New York, the Vinegar Factory[10] is a supermarket that has a rooftop greenhouse on the top of the store to produce some of their vegetables.

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[4] http://rooftopfarms.org/
[5] http://www.highergroundrooftopfarm.com/
[6] http://www.hkfarm.org/
[7] http://cloud9rooftopfarm.org/
[8] http://lufa.com/en/
[9] http://gothamgreens.com/
[10] http://www.elizabar.com/

- Lufa farms

| | | |
|---|---|---|
| **Type** | Commercial rooftop greenhouse | <br>Ahuntsic ©Lufa Farms<br><br>Laval ©Lufa Farms |
| **Name** | Lufa Farms | |
| **Location** | Montreal,<br>Canadà | |
| **Area** | 2,900 m$^2$ – 3,900 m$^2$ | |
| **Year** | 2010 - 2013 | |
| **Building type** | Former warehouse (Ahuntsic)<br>Industry (Laval) | |
| **Supply-chain** | CSA<br>Retailers<br>On-line sale | |
| **Produce** | Varieties of greens and microgreens, tomatoes, cucumber, pepper and basil. | |
| **Management** | Polyculture greenhouse with differentiated thermal areas, soil and hydroponic production with water re-circulation systems,<br>integrated pest management, chemical free production, LED lighting | |

- Gotham greens

| | | |
|---|---|---|
| **Type** | Commercial rooftop greenhouse | <br>Greenpoint ©Gotham Greens<br><br>Gowanus ©Gotham Greens |
| **Name** | Gotham Greens | |
| **Location** | Brooklyn, NY,<br>United States | |
| **Area** | 1,400 m$^2$ | |
| **Year** | 2011 | |
| **Building type** | Former warehouse (Greenpoint)<br>Supermarket (Gowanus) | |
| **Supply-chain** | Retailers and restaurants | |
| **Produce** | Varieties of greens (lettuce, chard, bok choy), tomatoes and basil | |
| **Management** | Hydroponic production with water re-circulation systems,<br>integrated pest management, chemical free production, LED lighting | |

Notwithstanding the lack of commercial initiatives in Europe, some companies are developing a rooftop greenhouse market to promote this type of urban agriculture. Urban Farmers[11] (Switzerland) and ECF Farmsystems GmbH[12] (Germany) are two companies that have designed rooftop greenhouse technology. In both cases, the companies have focused on the use of aquaponics, which combined hydroponic vegetables production with aquaculture by re-circulating the water between the activities (Figure 1.10). At the research scale, the feasibility of local production through integrated RTGs (i-RTGs), which can exchange metabolic flows with

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[11] http://urbanfarmers.com/

[12] http://www.ecf-farmsystems.com/

the building, is being tested in the RTG-Lab of the Universitat Autònoma de Barcelona in Bellaterra (Spain) (one of the case studies which is described in Chapter 2).

***Figure 1.10.*** *Demonstrative pilots of Urban Farmers and ECF Farmsystems.*

*Source: ©Urban Farmers and ©ECF Farmsystems*

### *1.3.4. Specific opportunities and challenges*

Beyond the opportunities related to urban agriculture and local production, urban rooftop farming (URF) offers specific opportunities toward urban sustainability. However, these types of urban food systems also have to overcome some challenges.

#### (i) Opportunities

Specific opportunities of urban rooftop farming are related to their situation on buildings and the technological innovation. URF has the capacity to optimize the urban space by taking advantage of currently unused spaces in cities: rooftops. The implementation of such systems is a way to revaluate these spaces that can become a source of urban resources and a place for new businesses (Cerón-Palma et al. 2012; Specht et al. 2014; Freisinger et al. 2015; Thomaier et al. 2015). At the city scale, URF can increase the multifunctionality of buildings and neighborhoods by recovering the food production function (Arosemena 2012). The use of these already constructed spaces for food production also reduces pressure to fertile soil in farmland areas (Droege 2012). Rooftop gardens can also help on the re-naturalization of cities and the contribution to urban biodiversity (Orsini et al. 2014), which is of great interest in the urban planning of high dense areas where the development of green areas and parks is constrained due to scarce land availability.

Rooftop farming may become an innovative way of urban agriculture by taking advantage of metabolic flows from the building. The farming system and the building can interact by exchanging resources and closing flows. In soil production, the organic waste from the households can be converted into compost to fertilize the crops. The water flows (rainwater, wastewater) from the building can be used as a source to satisfy the water requirements of the crops. Rooftop greenhouses offer larger opportunities towards a synergic metabolism with buildings. The residual heat and $CO_2$ from the building can be introduced in the greenhouse to improve the environmental conditions and increase the crop yield. This technological innovation can led not only to the production of high quality and environmentally-friendly food products but also to a growing interest of investors (Cerón-Palma et al. 2012; Specht et al. 2014; Freisinger et al. 2015; Thomaier et al. 2015).

### (ii) Challenges

As a novel and complex system, urban rooftop farming may have to overcome diverse challenges prior to a large-scale implementation. Food production is a new use of rooftops which is still not included in the legal framework. The use of rooftops is commonly determined in the zoning, which must be modified to implement such activities (Freisinger et al. 2015). Furthermore, the implementation of farming installation on roofs may ensure the safety of the building infrastructure, reducing the risks of overloading (Cerón-Palma et al. 2012). Thus, policymakers may develop instruments to include these new urban food systems in the urban policy to facilitate the URF implementation while ensuring the compliance with zoning and building requirements.

Barriers are also tied to the economic balance of URF systems, particularly for rooftop greenhouses. The needed investment of the activity is pointed out as a challenge (Cerón-Palma et al. 2012; Specht et al. 2014), limiting this type of URF to commercial projects. Furthermore, the complexity of farming practices (e.g., hydroponics) is also highlighted as a potential challenge to develop a local food sector based on such systems, not only from the economic perspective but also from the availability of trained urban farmers (Cerón-Palma et al. 2012).

## 1.4. Motivations of this dissertation

The implementation of urban rooftop farming (URF) has grown in developed countries although geographically concentrated. As urban agriculture, urban rooftop farming addresses multiple sustainability issues that involve a great number of urban stakeholders, leading into an unbalanced implementation that has multiple natures and aims. A comprehensive assessment of the deployment of such projects is required to identify the optimal context for the implementation of URF, as well as the environmental and economic balances of URF systems.

Some studies have assessed the barriers and opportunities behind rooftop farming systems, through round-tables with experts (Cerón-Palma et al. 2012) and reviewing the literature (Specht et al. 2014). However, there is a need to deepen in the knowledge, conceptualizations and perceptions of the stakeholders involved in the implementation processes of both urban agriculture and rooftop farming to better understand the potential of URF in qualitative terms: benefits, risks and challenges associated to the implementation of urban rooftop farming.

The location of rooftop farming projects is a challenge for a large-scale implementation of URF, particularly for rooftop greenhouses. Although some studies have approached the quantification of the URF potential (Berger 2013; Orsini et al. 2014), there is a need to further develop tools to support the identification and quantification of optimal spaces for the different types of URF by considering a multicriteria set that includes all the barriers and challenges of these innovative systems. Furthermore, the assessment of the quantitative potential of URF may also include sustainability indicators to support decision-making processes, such as in urban planning.

Notwithstanding that several sustainability benefits are expected from urban rooftop farming (Cerón-Palma et al. 2012; Specht et al. 2014), literature has limited its attention to the evaluation of the agronomic and biodiversity potential of URF (Whittinghill et al. 2013; Orsini et al. 2014; Freisinger et al. 2015). Furthermore, the quantitative assessment of urban agriculture has not paid attention to the environmental burdens of these systems, beyond relying on literature data from conventional farming practices (Kulak et al. 2013). The quantitative valuation of the environmental and economic performance of different types of urban rooftop farming can shed light on the contribution to the urban sustainability of such systems, as well as to provide data for the selection of URF types and the design of projects.

This dissertation aims to cover these research gaps thereby contributing to improve the knowledge on urban sustainability and the role of local food systems as well as to the understanding of the development process of urban agriculture and rooftop farming projects in developed countries.

## 1.5. Objectives of this dissertation

The goal of this dissertation is to assess the implementation of urban rooftop farming from a sustainability perspective. To do so, two main research questions are addressed throughout the thesis:

- ***Question 1:*** What is the potential of urban rooftop farming in qualitative and quantitative terms?
- ***Question 2:*** What are the environmental impacts and economic costs of urban rooftop farming systems?

The following specific objectives were defined to explore these questions:

- **Objective I** – To evaluate the potential implementation of urban rooftop farming in Mediterranean cities from a stakeholders' perspective (Chapter 3).
- **Objective II** – To develop a tool for the quantification and assessment of the potential implementation of rooftop greenhouses (Chapter 4).
- **Objective III** – To quantify and evaluate the potential implementation of rooftop greenhouses in industrial and retail parks (Chapter 4 and 5).
- **Objective IV** – To quantify the environmental impact and economic costs of rooftop greenhouses (Chapter 6 and 7).
- **Objective V** – To quantify the environmental impact and economic costs of community rooftop gardens (Chapter 8).
- **Objective VI** – To quantify the environmental impact of private rooftop gardens (Chapter 9).
- **Objective VII** – To revisit and develop the life cycle methodology for the assessment of urban foods as local systems (Chapter 9).

This objectives aims to answer the global research questions as follows:

| **Research question** | **Objectives** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **I** | **II** | **III** | **IV** | **V** | **VI** | **VII** |
| *Question 1:* What is the potential of urban rooftop farming in qualitative and quantitative terms? | ● | ● | ● | | | | |
| *Question 2:* What are the environmental impacts and economic costs of urban rooftop farming systems? | | | | ● | ● | ● | ● |

# Chapter 2

# Materials and methods

Picture: *Soil materials for rooftop farming (París, France)*
*(©Esther Sanyé-Mengual)*

# Chapter 2

This chapter details the methodological framework of this dissertation by defining the methods and tools employed and describing the main characteristics of the case studies.

## 2.1. Methods

This dissertation develops a sustainability assessment of urban rooftop farming (URF). To do so, an interdisciplinary methodological framework is here proposed. Figure 2.1 illustrates the different tools integrated in the sustainability assessment, which results into a combination of tools from the disciplines of social science research, geography, environmental science and economy. The assessment is performed at two main scales: at the city scale and at the system-product scale.

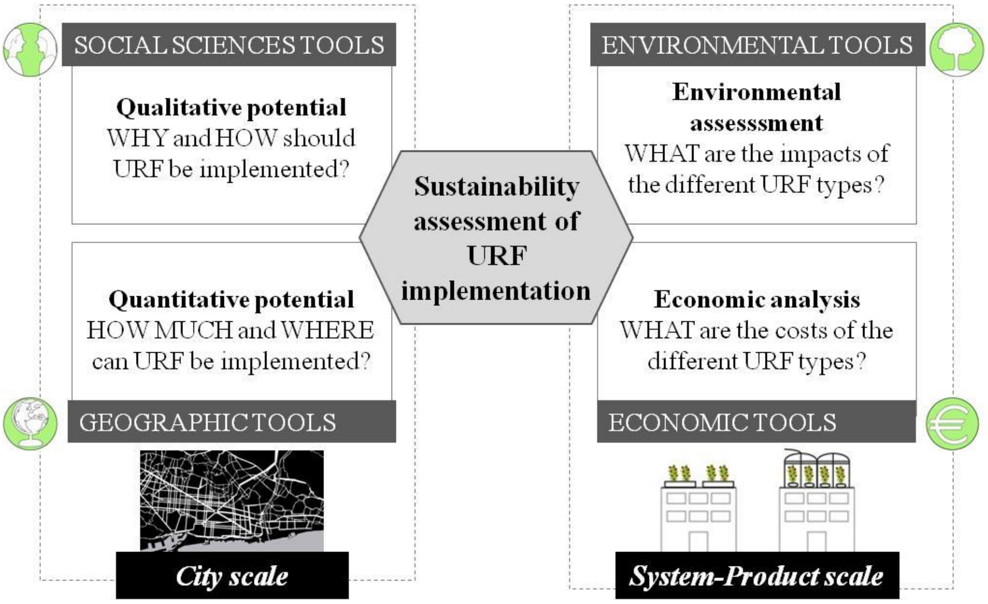

***Figure 2.1.*** *Overview of the interdisciplinary methodological framework of this dissertation.*

The approach is based on the different specifications of URF as a novel strategy towards urban sustainability and aims to answer essential questions regarding its implementation:

- As a novel strategy, social science research is used to interact with the different stakeholders involved in the development and implementation of URF with the aim of discovering its potential in qualitative terms.
  - Why should URF be implemented? The background of URF, the interests of the different stakeholders and the opportunities associated to URF are key issues.
  - How should URF be implemented? The potential URF models and users, the challenges and needed actions may be identified.
- As an urban strategy, geographic tools are used to quantify the potential implementation at different scales.

  - Where can URF be implemented? How much URF can be implemented? The identification of the optimal spaces where URF can be developed and the quantification of the potential implementation are essential when defining programs, urban strategies and planning actions.

- As a sustainable strategy, environmental and economic tools are used to quantify and compare different URF types.
  - What are the impacts of the different URF types? The evaluation of the environmental impacts shows the benefits of the different models of URF. Environmental data can define the potential of URF as local food systems, inform consumers about these new food products and support decision-making processes of URF implementation.
  - What are the costs of the different URF types? Since URF can be commercial, public or private, the quantification of the costs of the different URF types can inform stakeholders when starting up projects and public entities when defining programs, urban strategies and planning actions.

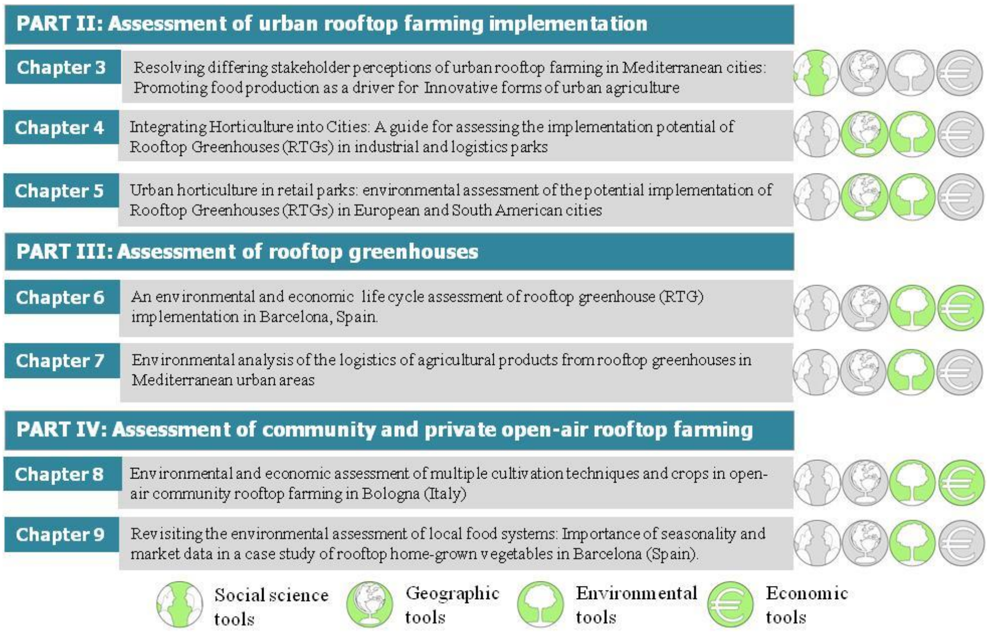

***Figure 2.2.*** *Overview of the methods used in each chapter of this dissertation.*

Figure 2.2 shows the tools used in each chapter, which follows this interdisciplinary design. Chapter 3 unravels the perception of stakeholders and identifies the potential implementation of URF in qualitative terms through social science research. Chapter 4 proposes a guide to quantify the feasible rooftop area for URF implementation and their environmental benefits by combining geographic information systems (GIS) and life cycle assessment (LCA). Chapter 4 and 5 employ this guide to quantify the potential implementation of URF in industrial and retail parks. Chapter 6, 7, 8 and 9 quantify the environmental impacts and economic costs of different urban rooftop farming systems: rooftop greenhouses, community rooftop gardens and private rooftop gardens, by applying the LCA and life cycle costing (LCC) methods.

### *2.1.1. Social science tools*

Data collection through qualitative research methods was performed to identify the stakeholders' perceptions and narratives thereby deepening in the implementation processes of URF (e.g., benefits, constraints, challenges, users and use models). Among social science research methods, a qualitative interview study was identified as the most accurate way to approach this objective since this type of tools support the integration of multiple perspectives and the description of processes (Weiss 1995).

Interviews are conversations between people, where the interviewer aims to obtain information from the interviewee(s) (i.e., informant). They range from unstructured interviews where there is no script and the informant leads the conversation to structured interviews that strictly follow a list of questions. Between them, semi-structured interviews are performed following a prepared questionnaire but giving the flexibility to the informant to address other issues (Dunn 2005; Clifford et al. 2010).

The social research process (Chapter 3) followed five main steps, as illustrated in Figure 2.3:

- Goal and scope: the research questions needed to be addresses and the system under study were first defined in order to determine the goal and scope of the research process.
- Secondary data collection: the contextualization of the case study and the topic was performed through collection of secondary data, such as news, laws, reports, projects or internet sources.
- Interview design: the design of the interview consists of elaborating the questionnaire to guide the semi-structured interview and defining the sample of interviewees. The definition of the sample was performed in two main steps: configuration of a stakeholder map, based on the analysis of the secondary data, and snowball sampling, where interviewees suggested other candidates due to their importance on the topic under assessment in the study area.
- Data collection: primary data was collected through the performance of the interviews and the fieldwork carried out during the visits to the different institutions, entities and projects for the interviews. Interviews were recorded while fieldwork provided extra information compiled as notes.
- Analysis: the transcription of the interviews and fieldwork notes were used as the basis for the analysis. Grounded theory techniques were used to analyze the qualitative data in a systematic way in order to reduce the risk of predominance of pre-defined concepts during this stage (Corbin and Strauss 1990; Kuckartz 2012). This material was coded line-by-line, generating a text divided into concepts and categories, which was later re-assembled according to theoretical concepts in order to create discourses thereby envisioning emerging theories.

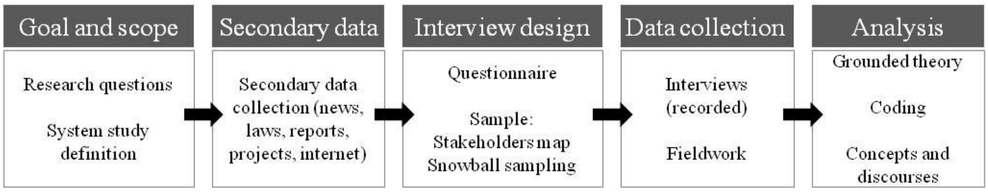

**Figure 2.3.** *Qualitative research process through semi-structured interviews.*

### 2.1.2. Geographic tools

Geographic Information Systems (GIS) are digital softwares and databases which support the process, storage and analysis of spatial data (Bernhardsen 2002). At the planning scale, GIS are essential for supporting decision-making processes (Bernhardsen 2002). GIS have been widely used in environmental science research (e.g., Haslett 1990; Vine et al. 1997; Maantay 2002). Furthermore, GIS were a key tool for identifying the potential of urban agriculture, such as the UA mapping performed in Oakland by McClintock et al. (2013) or in Chicago by Taylor and Taylor Lovell (2012).

In this dissertation, geographic information systems were used to generate the rooftop database, which are the basis for quantifying the potential of urban rooftop farming. The creation of the rooftop database was a three-step process, which is detailed in Chapter 4 and can be summarized as in Figure 2.4. The free software GVSig[13] was used for this purpose.

The use of GIS was essential for:

- working at the planning scale (i.e., retail or industrial parks),
- accessing spatial data (e.g., area, sunlight)
- generating new data (e.g., material, rooftop type)

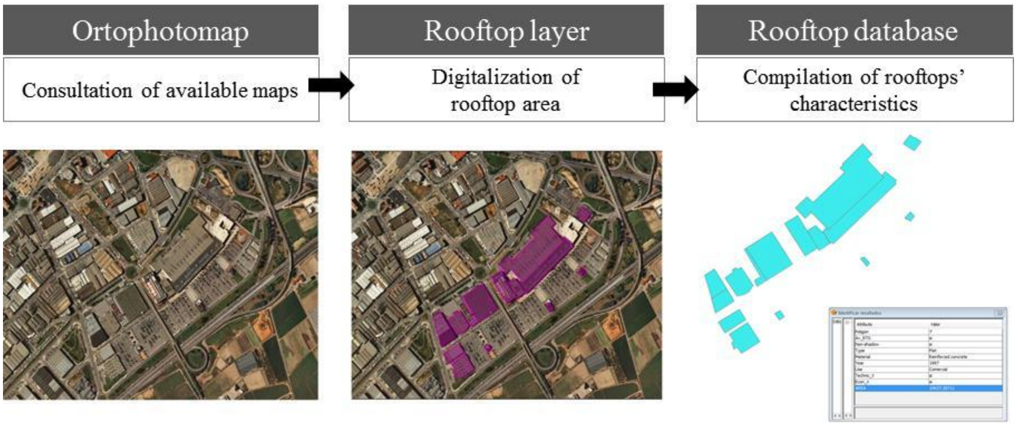

**Figure 2.4.** *Geographic information systems (GIS) processes for generating the rooftop database to compile data of urban planning pieces (e.g., retail parks).*

### 2.1.3. Environmental tools

The quantification of the environmental impacts of rooftop farming systems was done through the application of the life cycle assessment (LCA) (ISO 2006a) method, defined as:

> *"LCA is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (i.e., consecutive and interlinked stages of a product system, from raw materials acquisition or generation from natural resources to final disposal)"* (ISO 2006a)

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[13] http://www.gvsig.com/en

### (i) Life cycle assessment

The ISO 14040 (2006a) - 14044 (ISO 2006b) standards proposed a four-stage method for the development of an LCA, as illustrated in Figure 2.5.

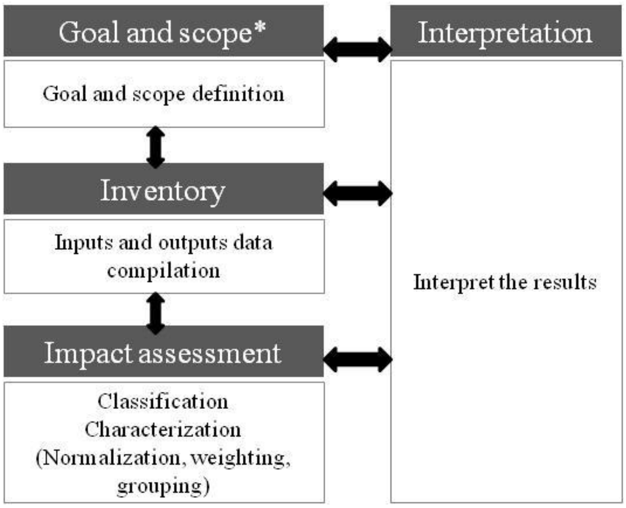

***Figure 2.5.*** *Phases of the life cycle assessment method.*

*Own elaboration from ISO (2006).*The ILCD Handbook describes "Goal and scope" as two separate stages.*

#### (a) Goal and scope

The goal definition establishes the decision-context(s) and intended application(s) of the LCA study, setting the framework for its development. In this stage, the following aspects of the LCA study are determined:

- the objectives
- the application(s)
- the target audience
- the limitations

The scope definition focuses on the object of the study by describing and detailing:

- the system or process under assessment, in terms of function, functional unit and reference flows
- the LCI modelling framework and the handling of multifunctional processes and products (allocation procedures)
- the system boundaries, the completeness requirements and cut-off rules
- the LCI data quality requirements
- the LCIA impact categories and methods to be used

During the goal and scope phase, the definition of the functional unit, the modelling of multifunctional processes and the selection of the LCI modelling framework are key aspects.

The function of the system and the functional unit considered are central in an LCA study (EC-JRC 2010). The functional unit quantifies the qualitative and quantitative aspects of the function(s) of the system under assessment, by providing information about “what”, “how much”, “how well” and “for how long”. The definition of the functional unit is particularly essential in comparative studies. The LCI data is quantified for the defined functional unit of the study.

When different products are obtained (i.e., co-products or by-products), the environmental burdens of the process or system need to be allocated over the different outputs or functions. The ISO 14044 (ISO 2006b) prioritizes the application of different allocation procedures as follows:

- When possible, allocation should be avoided by:
  - First option: Divide the unit process of the system to be allocated into two or more sub-processes, where the different co-products are performed
  - Second option: Expand the system in order to include the additional functions provided by the co-products
- When allocation is unavoidable, the inputs and outputs of the system (i.e., and the resulting environmental burdens) should be partitioned between the resulting products or functions according to physical relationships (mass), economical relationships (revenues) or other relationships, such as the energy-content.

The modelling framework of an LCI can be attributional (A-LCA) or consequential (C-LCA) (Heijungs 1997; Tillman 2000; Weidema 2003; Thomassen et al. 2008). The UNEP/SETAC-Life cycle initiative (2011a) defined the two LCA approaches as follows:

- A-LCA is a “system modelling approach in which inputs and outputs are ttributed to the FU of a product system by linking and/or partitioning the unit processes of the system according to a normative rule”
- C-LCA is a “system modelling approach in which activities in a product system are linked so that activities are included in the product system to extent that they are expected to change as a consequence of a change in demand for the FU”

Thus, A-LCA aims to describe the “status quo” of a system based on a specific FU by establishing static system boundaries that only include the processes and material flows directly used by the system, using average data for the LCI and not considering the market effects. On the contrary, C-LCA estimates the “consequences” on the environmental impacts of a system based on a change in the FU by establishing expanded system boundaries that include the processes and material flows both directly and indirectly used by the system, using marginal data for the LCI and including the market effects (Guinée et al. 2002; Weidema 2003; Rebitzer et al. 2004; Thomassen et al. 2008). Regarding multifunctionality, the C-LCA always applies the system expansion, while A-LCA follows ISO 14044 recommendations.

### (b) Life cycle inventory

The life cycle inventory is a compilation of all the inputs and outputs of the system under assessment. Thus, the LCI includes all the resources consumed and all the emissions released into the environment throughout the entire life cycle of a system, process or product. Inputs can be categorized as resources from nature (e.g., mineral extraction, water) or resources from the technosphere (e.g., plastics, electricity). Outputs are differentiated among emissions to the environment (air, water, soil) and to the technosphere (wastes to treatment).

This stage consists of collecting data, identifying the relevant and non-relevant elements (e.g., cut-off criteria can be applied), ensuring the mass and energy balance, and applying allocation procedures when needed. LCI data can be primary or foreground (e.g., fieldwork, company data, project data) and secondary or background (e.g., previous studies, databases). In this stage, the availability of data is crucial and the global and regional life cycle databases play a key role. Among them, ecoinvent (Swiss Center for Life Cycle Inventories 2010) is the largest LCI database and the most used worldwide.

### (c) Life cycle impact assessment

The life cycle impact assessment (LCIA) stage translates the LCI results to environmental impacts by applying a determined impact assessment method (EC-JRC 2010). LCIA methods can be at the midpoint and at the endpoint, depending on the level at which the impacts are quantified (UNEP/SETAC Life Cycle Initiative 2011b). The midpoint level is a problem-oriented approach, where the impact is close to the intervention (e.g., global warming in terms of kg of $CO_2$ eq.), while the endpoint level is a damage-oriented approach where indicators are expressed in recognisable values to society, which are also called areas of protection: human health, natural environment and natural resources (e.g., effects of global warming in terms of DALY) (EC-JRC 2010).

According to the ISO 14040 (2006a), the LCIA consists of two mandatory steps, classification and characterisation, and optional ones, normalization, weighting and grouping. The first step of an LCIA is the classification of the inputs and outputs (LCI) to group them in different impact categories or indicators, thereby identifying to which environmental effect each flow is contributing (e.g., carbon dioxide emissions contribute to global warming). As a second step, the characterisation aims to calculate the value of the environmental impact by using specific characterisation factors from the literature, databases or LCIA methods (EC-JRC 2010) (e.g., methane emissions impact the equivalent to 24kg of carbon dioxide emissions to global warming). These two mandatory steps provide the LCIA results.

Additionally, LCIA results can be normalized, aggregated or weighted. Normalization compares the value of the indicator to a reference in order to know the relevance of the results within a specific context. Grouping is a semi-quantitative process which sorts and ranks the results across impact categories, thereby establishing priorities among the different environmental indicators. Weighting is aimed to convert the indicator results of different impact categories by using numerical factors based on value-choices and, commonly, aggregate the weighted indicator values. Both grouping and weighting are used to observe the importance of indicators.

### (d) Interpretation

The final stage of an LCA study consists of interpreting the LCI and LCIA results together in order to unravel the findings and main conclusions, and provide recommendations to support decision-making processes, when needed. In this stage, the iterative nature of LCA it is observed, as the interpretation of the results may lead to a revision of the rest of the LCA stages (e.g., redefining the functional unit or choosing other LCIA methods). Furthermore, the interpretation must be a transparent process that considers the choices performed among the LCA study while trying to minimize subjectivity.

### (ii) LCA specifications of this dissertation

The LCA specifications regarding the functional unit and system boundaries (goal and scope), the data sources (inventory) and the methods and indicators (impact assessment) are here described.

**(a) Goal and scope: Functional unit and system boundaries**

The functional units used in this dissertation were:

- **1 $m^2$** when assessing the cultivation systems and structures (e.g., rooftop greenhouse)
- **1 kg** when assessing food products (e.g., tomato)

The system boundaries used in this dissertation were:

- **Cradle-to-farm gate**: from the extraction of raw materials to the harvesting of food products.
- **Cradle-to-consumer**: from the extraction of raw materials to the retail of food products.
- **Cradle-to-grave**: from the extraction of raw materials to the end of life management of products.

**(b) Life cycle inventory: Data sources**

Various foreground and background data sources were used to complete the life cycle inventories of the different studies. Table 2.1 shows the type of data, the sources and their use in the different chapters.

*Foreground data:*

- Cultivation systems data: the structures and equipment needed for the horticultural production (e.g., greenhouse) were collected from the construction project (i.e., rooftop greenhouse), from the funding project (i.e., community rooftop garden) or from fieldwork (i.e., private rooftop garden).
- Production: experimental crop data was used for characterising this stage for the community and private rooftop garden systems.
- Distribution and retail: data from the farm gate to the consumer was collected from statistics of food distribution centres, interviews with managers of food distribution companies and surveys performed to fruit and vegetable retailers.

*Background data:*

- The ecoinvent database (Swiss Center for Life Cycle Inventories 2010) was used to complete LCI data regarding the materials extraction and processing, transportation and end of life treatments.
- The LCA Food database (Nielsen et al. 2003) was the source of LCI data on fertilizers and pesticides production.
- The EUPHOROS project (Montero et al. 2011) provided LCI data on conventional protected horticulture production for Spain (i.e., soil-less production in multitunnel greenhouses) and The Netherlands (i.e., soil-less production in VENLO greenhouses).

*Table 2.1.* *LCI data sources used in this dissertation*

| Data type | Life cycle stage | Source | Chapters | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 4 | 5 | 6 | 7 | 8 | 9 |
| **Foreground data** | Production | ICTA-ICP construction project data | | | ● | | | |
| | | GreenHousing / HORTIS project data | | | | | ● | |
| | | Fieldwork data | | | | | | ● |
| | | Crops experimental data | | | | | ● | ● |
| | Distribution | Distribution centre data | ● | ● | ● | ● | | ● |
| | | Distribution company data | ● | ● | ● | ● | | |
| | Retail | Food retailers survey | ● | ● | ● | ● | | |
| **Background data** | All stages | Ecoinvent 2.2 database | ● | ● | ● | ● | ● | ● |
| | | LCA Food | ● | ● | ● | ● | ● | ● |
| | | EUPHOROS project | ● | ● | ● | ● | | |

### (c) Life cycle impact assessment: Methods and indicators

SimaPro (PRé Consultants 2011) was the software tool employed for the impact assessment stage. Multiple LCIA methods and indicators were used in the environmental assessment chapters of this dissertation, as specified in table 2.2. Impact assessment is a field under development in LCA. To achieve a higher robustness of LCIA results, methods and indicators were updated as also recommended by global guidelines (e.g., EC-JRC, 2010). During the development of this dissertation the use of the CML-IA method was switched to the ReCiPe method due to the improvement of LCIA methodologies. In fact, ReCiPe method further developed the methodologies built in the CML-IA and Eco-indicator 99 methods, which were the first ones in proposing midpoint and endpoint LCIA methods, respectively (Goedkoop et al. 2009). Anyway, results from Chapter 7, which were calculated using CML-IA 2001 method, were used and updated to the ReCiPe method in Chapter 6.

The criteria for choosing the environmental indicators were the following:

- Global warming (Climate change in ReCiPe) was selected due to the importance of this environmental issue at the global scale and the awareness of the academia, the industry and the general public.
- Cumulative energy demand (CED) was always accounted for due to the relevance of transportation and supply-chains in this dissertation.
- In order to avoid trade-offs between environmental effects, other environmental indicators from the CML-IA 2001 or the normalized midpoint value of ReCiPe indicators were commonly used to show the effects of the systems under assessment to other environmental issues.
- Water depletion had a key role in Chapter 8 where the water consumption strongly varied among the cultivation techniques under assessment.

***Table 2.2.*** *LCIA methods and indicators used in this dissertation*

| **Method** | **Indicator** | **Chapters** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **4** | **5** | **6** | **7** | **8** | **9** |
| CML-IA 2001 | Abiotic depletion | | | | ● | | |
| | Acidification | | | | ● | | |
| | Eutrophication | | | | ● | | |
| | Global warming | ● | ● | | ● | | |
| | Ozone layer depletion | | | | ● | | |
| | Human toxicity | | | | ● | | |
| ReCiPe | ReCiPe normalized | | | ● | | ● | |
| | Climate change | | | ● | | ● | ● |
| | Water depletion | | | | | ● | |
| Cumulative energy demand | Cumulative energy demand | ● | ● | ● | ● | ● | ● |

Tables 2.3, 2.4 and 2.5 compile the characteristics of the midpoint indicators of the CML-IA 2001 method (Guinée et al. 2002), the ReCiPe method (Goedkoop et al. 2009) and the cumulative energy demand (CED) (Hischier et al. 2010), respectively.

***Table 2.3.*** *LCIA indicators of the CML-IA 2001 method.*

| Indicator | Purpose |
|---|---|
| **Abiotic depletion potential<br>(ADP)** | *Aim:* Accounting for the loss of fossil and mineral resources, which affects the human welfare, human health and ecosystems health<br>*Method:* The fossil fuel and minerals inputs in the LCI are linked to mineral depletion potential factor of each commodity, which is based on the reserves availability.<br>*Unit:* kg Sb eq. |
| **Acidification potential<br>(AP)** | *Aim:* Accounting for the acidifying substance and the resulting impacts on soil, groundwater, surface water, organisms, ecosystems and materials (buildings).<br>*Method:* The emissions to air of acidifying substances in the LCI are linked to the acidification potential factor, calculated through the RAINS 10 model.<br>*Unit:* kg $SO_2$ eq. |
| **Eutrophication potential<br>(EP)** | *Aim:* Accounting for the eutrophying substances (i.e., macronutrients) and the resulting impacts due to excessive presence in nature compartments (air, water, soil).<br>*Method:* The emissions of eutrophying substances in the LCI are linked to the eutrophication potential factor, based on a stoichiometric procedure proposed by Heijungs et al. (1992).<br>*Unit:* kg $PO_4^{-3}$eq. |
| **Global warming potential<br>(GWP)** | *Aim:* Accounting for the substances that contribute to climate change.<br>*Method:* The emissions of greenhouse gases in the LCI are linked to the characterisation factors developed by the Intergovernmental Panel on Climate Change (IPCC) for a time horizon of 100 years.<br>*Unit:* kg $CO_2$ eq. |
| **Ozone layer depletion potential<br>(OLDP)** | *Aim:* Accounting for the loss of stratospheric ozone with increase the fraction of UV-B radiation that reaches the Earth's surface and the consequent impacts.<br>*Method:* The emissions to air of ozone depleting gases in the LCI are linked to the ozone layer depletion potential factors developed by World Meteorological Organisation (WMO).<br>*Unit:* kg CFC-11 eq. |
| **Human toxicity potential<br>(HTP)** | *Aim:* Accounting for the toxic substances and the resulting effects on the human environment.<br>*Method:* The emissions of substances in the LCI are linked to the human toxicity potential factor, based on the USES-LCA model.<br>*Unit:* kg 1.4-DB eq. |

*Based on Martinez Blanco, 2012; Starr, 2013; Guinée et al., 2001.*

***Table 2.4.*** *LCIA indicators of the ReCiPe method.*

| Indicator | Purpose |
|---|---|
| **Climate change (CC)** | *Aim:* Accounting for the infra-red radiative forces causing global warming<br>*Method:* The emissions to air of greenhouse effect gases in the LCI are linked to global warming potential factors for calculating their infra-red radiative force. Factors are obtained from IPCC (2007) and updates.<br>*Unit:* kg $CO_2$ eq. |
| **Ozone depletion (OD)** | *Aim:* Accounting for the stratospheric ozone concentration<br>*Method:* The emissions to air of ozone depleting substances (CFCs, halons, etc) in the LCI is linked to the ozone depletion potential factor. Factors are specified in Goedkoop et al. (2009).<br>*Unit:* kg CFC-11 eq. |
| **Terrestrial acidification (TA)** | *Aim:* Accounting for the concentration of acidifying substances<br>*Method:* The emissions to air of acidifying substances ($NO_x$, $NH_3$, $SO_2$) in the LCI are linked to acidification potential factors. Factors are based on EUTREND and SMART2 models. Factors are specified in Goedkoop et al. (2009).<br>*Unit:* kg $SO_2$ eq. |
| **Freshwater eutrophication (FE)** | *Aim:* Accounting for the concentration of eutrophying substances. In freshwater bodies the limiting substance is phosphorous and thus only nitrogen substances generate eutrophication.<br>*Method:* The emissions to water of N in the LCI are linked to eutrophication potential factors, which are calculated following the CARMEN model (fate of substances). Factors are specified in Goedkoop et al. (2009).<br>*Unit:* kg P eq. |
| **Marine eutrophication (ME)** | *Aim:* Accounting for the concentration of eutrophying substances. In seawater bodies the limiting substance is nitrogen and thus only phosphorous substances generate eutrophication.<br>*Method:* The emissions to water of P in the LCI are linked to eutrophication potential factors ($kg \cdot kg^{-1}$), which are calculated following the CARMEN model (fate of substances). Factors are specified in Goedkoop et al. (2009).<br>*Unit:* kg N eq. |
| **Human toxicity (HT)** | *Aim:* Accounting for the toxic substances that affect human health<br>*Method:* The emissions of toxic substances in the LCI are linked to human toxicity potential factors, which are calculated following the USES-LCA 2.0 model that is based on fate, exposure, effect and damage.<br>*Unit:* kg 1,4-DCB eq. |
| **Photochemical oxidant formation (POF)** | *Aim:* Accounting for the presence of substances that produce photochemical oxidation<br>*Method:* The emissions to air of NMVOC and $NO_x$ in the LCI is linked to the photochemical oxidant formation potential factor ($kg \cdot kg^{-1}$) of each substance. Factors are specified in Goedkoop et al. (2009), which are based on fate and effect of substances.<br>*Unit:* kg NMVOC eq. |
| **Particulate matter formation (PMF)** | *Aim:* Accounting for the presence of substance that forms particulate matter<br>*Method:* The amount of particulate matter substances ($PM_{10}$, $NH_3$, $SO_2$, $NO_x$) in the LCI is linked to the particulate matter formation potential factor of each substance. Factors are specified in Goedkoop et al. (2009), which are based on fate and effect of substances.<br>*Unit:* kg $PM_{10}$ eq. |
| **Terrestrial ecotoxicity (TET)** | *Aim:* Accounting for the potential fate and effect of toxic substances in terrestrial environments<br>*Method:* The emissions of toxic substances to air and soil in the LCI are linked to ecotoxicity potential factors, which are calculated following the USES-LCA 2.0 model that is based on fate, exposure, effect and damage. Exposure considers the |

| | |
|---|---|
| | density of urban settlements.<br>*Unit:* kg 1,4-DCB eq. |
| **Freshwater ecotoxicity (FET)** | *Aim:* Accounting for the potential fate and effect of toxic substances in freshwater bodies<br>*Method:* The emissions of toxic substances to soil and air of rural areas in the LCI are linked to ecotoxicity potential factors, which are calculated following the USES-LCA 2.0 model that is based on fate, exposure, effect and damage.<br>*Unit:* kg 1,4-DCB eq. |
| **Marine ecotoxicity (MET)** | *Aim:* Accounting for the potential fate and effect of essential metals in oceans<br>*Method:* The emissions of essential metals (Cobalt, Copper, Manganese, Molybdenum and Zinc) to ocean and sea water bodies in the LCI are linked to toxicity potential factors, which are calculated following the USES-LCA 2.0 model that is based on fate, exposure, effect and damage of each substance.<br>*Unit:* kg 1,4-DCB eq. |
| **Ionising radiation (IR)** | *Aim:* Accounting for the absorbed dose of radiation<br>*Method:* The amount of radionuclides of the LCI is linked to ionising radiation potential factor of each element. The model is based on Svenson exposure. Factors are specified in Goedkoop et al. (2009).<br>*Unit:* kg U235 eq. |
| **Agricultural land occupation (ALO)** | *Aim:* Accounting for the occupation of agricultural land during an specific period<br>*Method:* The land occupation of agricultural land uses in the LCI is valued according to the agricultural land occupation potential. Factors are specified in Goedkoop et al. (2009).<br>*Unit:* $m^2 \cdot y$ |
| **Urban land occupation (ULO)** | *Aim:* Accounting for the occupation of urban land during an specific period<br>*Method:* The land occupation of urbanised land uses in the LCI is valued according to the urban land occupation potential. Factors are specified in Goedkoop et al. (2009).<br>*Unit:* $m^2 \cdot y$ |
| **Natural land transformation (NLT)** | *Aim:* Accounting for the transformation of natural land to other uses<br>*Method:* The land transformation from natural land uses to other land uses from the LCI is valued according to the natural transformation land potential. Factors are specified in Goedkoop et al. (2009).<br>Unit: $m^2$ |
| **Water depletion (WD)** | *Aim:* Accounting for the depletion of freshwater bodies<br>*Method:* The freshwater use ($m^3$) from the LCI is linked to a water depletion potential factor based on the water source. Factors are specified in Goedkoop et al. (2009).<br>Unit: $m^3$ |
| **Mineral resource depletion (MRD)** | *Aim:* Accounting for the loss of grade (quality-yield relation) of mineral deposits<br>*Method:* The extraction of mineral resources of the LCI is linked to the mineral depletion potential factor of each commodity.<br>*Unit:* kg Fe eq. |
| **Fossil depletion (FD)** | *Aim:* Accounting for the lower heating value of fossil fuels<br>*Method:* The extraction of fossil resources of the LCI is linked to the energy content value of each fuel. Factors are obtained from the ecoinvent database (Frischknecht et al., 2007)<br>*Unit:* kg oil eq. |

*Based on Goedkoop et al., 2009.*

***Table 2.5.** LCIA indicator of Cumulative Energy Demand.*

| Indicator | Purpose |
|---|---|
| **Cumulative energy demand (CED)** | *Aim:* Account for the primary energy use<br>*Method:* The inputs of energy in the LCI are linked to the primary energy characterisation factors, which depend on the energy resource: non-renewable (fossil and nuclear), renewable (biomass, wind, solar, geothermal, water).<br>Unit: MJ |

*Based on Hischier et al., 2010; Martinez Blanco, 2012; Starr, 2013)*

### 2.1.4. Economic tools

The economic costs of URF types were accounted for by following the Life Cycle Costing (LCC) method (ISO 2008), which is defined as:

> *"A tool and technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial capital costs and future operational and asset replacement costs, through to end of life, or end of interest in the asset – also taking into account any other non-construction costs and income, defined as in scope"* (ISO 2008)

#### (i) Life cycle costing method

UNEP/SETAC Life Cycle Initiative (2011) has recently published guidelines for the implementation of a four-phase LCC method that follows the ISO 14040 standard (see Figure 2.6), based on the methodological recommendations and code of practice previously published (Hunkeler et al. 2008; Swarr et al. 2011). Although the four-phase method follows the pattern of the environmental LCA, the impact assessment stage is here converted into an aggregation step where costs are grouped by categories.

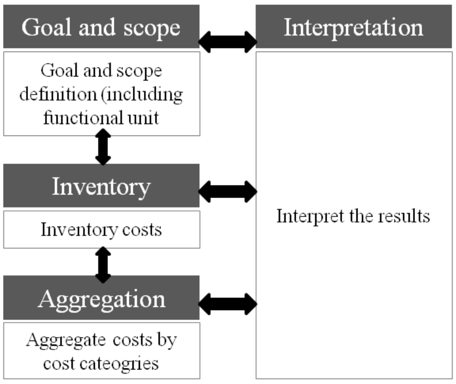

***Figure 2.6.** Phases of the life cycle costing method.*

*Own elaboration from UNEP/SETAC Life Cycle Initiative, 2011.*

According to the UNEP-SETAC guide on life cycle sustainability assessment (UNEP-SETAC 2011), three types of life cycle costing can be developed depending on the scope:

- **Conventional LCC** incorporates only private costs and benefits. Then, that is an LCC internal to the system under assessment (e.g., the company)

- **Environmental LCC** incorporates in the LCC external relevant costs and benefits anticipated to be privatized
- **Societal LCC** monetize all private and external costs and benefits

### (ii) LCC practices

Since the accumulation of costs and benefits of systems is the least standardized of the life cycle tools (Swarr et al. 2011), LCC can be performed by using different economic approaches. The most common practices in the literature are here listed and exemplified:

- The Cost-Benefit Analysis (CBA) approach is a common practice in LCC. However, some LCC studies accounted for only the cumulative costs of the system for the entire lifespan, without considering economic benefits. Traverso et al. (2012) compared the life cycle costs of photovoltaic modules in two European countries.
- Financial tools are also used in LCC. Discount rates are commonly used to estimate future prices along the entire lifespan of the system. The studies that consider the variability of costs show the values in terms of Net Present Value (NPV) or Net Present Cost (NPC). Peri et al. (2012) considered a discount rate of 6% in order to update the investment costs along the entire lifespan of a green roof system.
- LCC can be displayed through indicators that quantify the costs of the different life cycle stages. Martínez-Blanco et al. (2014) used three different indicators to illustrate the costs of each of the life cycle stages included in the study: fertilizer price (production), transportation cost (distribution) and fertilizer application (use).
- Societal LCC includes environmental and social benefits of systems that are monetized to be included as revenue. Bianchini and Hewage (2012) accounted for the costs of green roof systems while including the social functions (e.g., recreational space) and environmental services (e.g., urban heat island decrease) as economic benefits.
- When integrated into a life cycle sustainability assessment (LCSA), LCC is commonly a conventional LCC in order to avoid double-counting, as recommended by Swarr et al. (2011). Vinyes et al. (2012) performed a LCSA of different management models of used cooking oils. In the individual LCC assessment, the author quantified the costs savings of reducing the $CO_2$ emissions using the cost of $CO_2$ abatement techniques. However, the LCC values were limited to internal costs (i.e., conventional LCC) in the global presentation of LCSA results, since the benefits of global warming mitigation were already accounted for in the environmental LCA.

### (iii) LCC specifications of this dissertation

In this dissertation, life cycle costing was applied as a conventional LCC since it was always used together with an environmental LCA. The quantification of the economic balance followed a Cost-Benefit approach (CBA) and, thus, the cumulative costs of the systems were balanced with the cumulative revenues, when generated (i.e., commercial-oriented activities).

Rather than showing the costs of the entire lifespan of a product, LCC results were always showed for the timeframe considered in the functional unit of the analysis (e.g., commonly one production year or one crop period). However, discount rates were used in the analysis to update prices of different years when needed.

Within the life cycle of products, actors can have different perspectives of costs (Hunkeler et al. 2008; Swarr et al. 2011). In fact, the stakeholder changes according to the perspective of the assessment. For example, in the assessment of food products, the producer is the key actor in a cradle-to-farm gate scope while the retailer is the focus in a cradle-to-consumer analysis. This issue must be clarified in the methodological approach of LCC and it is specified in the methods section of each chapter.

Table 2.6 shows the two LCC indicators used in the economic assessment and the purpose of each indicator. While the total cost indicator is used for all types of URF (Chapters 6 and 8), the total profit indicator is only applied to commercial-oriented systems (Chapter 6).

***Table 2.6.*** *Economic indicators used in this dissertation*

| Indicator | Purpose |
|---|---|
| Total Cost (TC) | The indicator aims to show the cumulative cost of the life cycle stages of the system under assessment for a determined functional unit.<br>Depending on the scope of the analysis, this indicator shows production cost (cradle-to-farm gate), retail cost (cradle-to-consumer) or final product cost (cradle-to-grave).<br>*Unit:* € |
| Total Profit (TP) | The indicator aims to show the value of the product from a cost-benefit perspective. Thus, the indicator balances the cumulative costs and the cumulative benefits (i.e., revenues) of the system under assessment for a determined functional unit.<br>Depending on the scope of the analysis, this indicator shows production profit (cradle-to-farm gate) or retail profit (cradle-to-consumer).<br>*Unit:* € |

## 2.2. Case studies

URF can be implemented in different forms and for multiple purposes. With the aim of illustrating the diverse environmental and economic profile of URF systems, different types of rooftop production where assessed in this dissertation. Three case studies that represented various natures of rooftop farming were assessed in this dissertation (Figure 2.7):

- a rooftop greenhouse in a research institute: the Rooftop Greenhouse Lab (RTG-Lab) of the ICTA-ICP building in Bellaterra (Spain)
- a community rooftop garden with open-air production in a social housing of the city of Bologna (Italy)
- a private rooftop garden with open-air soil-less production in the city centre of Barcelona (Spain)

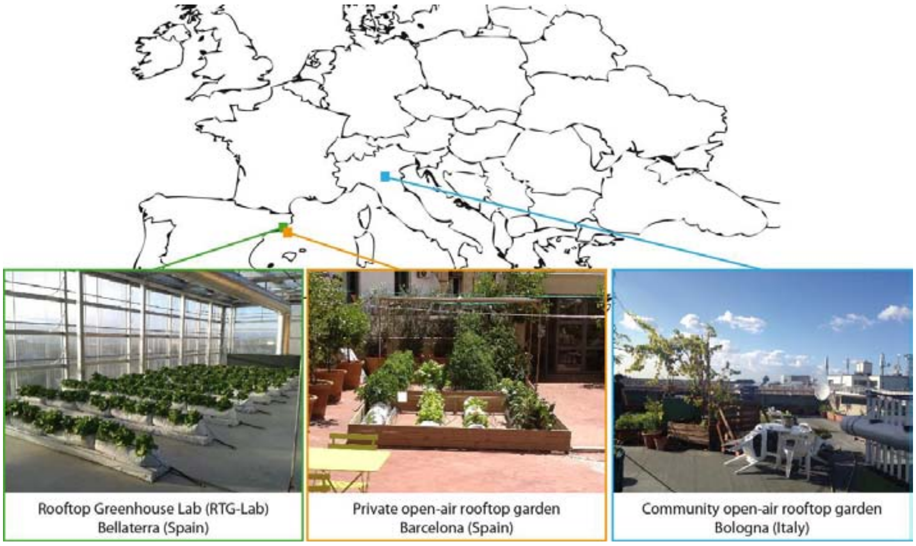

***Figure 2.7.*** *Location of the case studies under assessment.*

Figure 2.8 compiles the characteristics of the case studies according to the URF types defined by the Association of Vertical Farming[14] in terms of integration, exposure, purpose and growing medium (soil-less was added as a new category), and specifies the location, users and crops of each case study. The chapters 3-9 analyse the different URF types with specific tools. Chapter 3 assesses the qualitative potential of all URF types. Chapter 4 and 5 quantifies the potential implementation of RTGs, since this is the most limiting type of URF due to space requirements. Environmental assessment is performed for all types of URF in chapters 6-9. Economic assessment is performed for RTGs (Chapter 6) and community rooftop garden (Chapter 8). The case studies used in this dissertation are described in the following sections.

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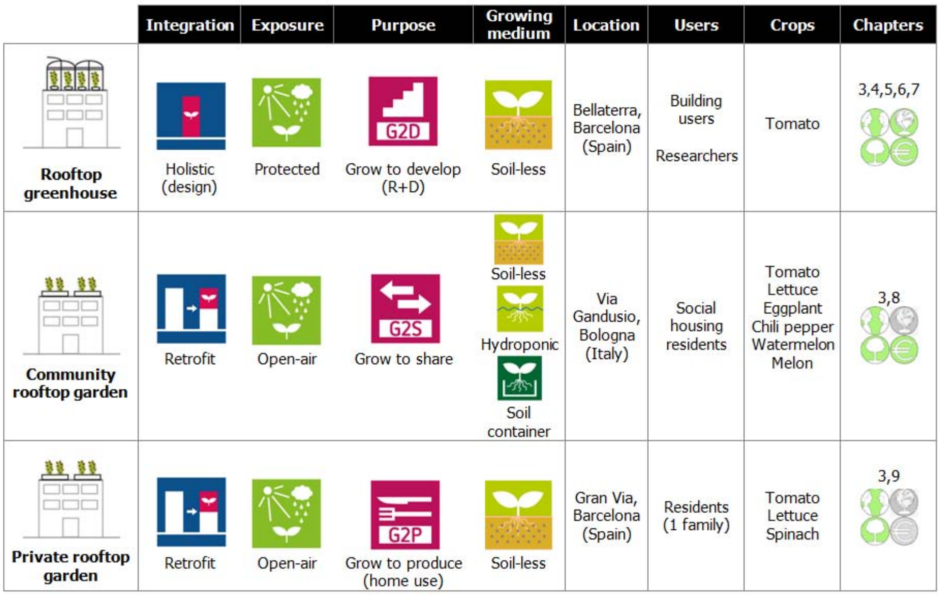
[14] http://vertical-farming.net/



| | Integration | Exposure | Purpose | Growing medium | Location | Users | Crops | Chapters |
|---|---|---|---|---|---|---|---|---|
| **Rooftop greenhouse** | Holistic (design) | Protected | G2D<br>Grow to develop (R+D) | Soil-less | Bellaterra, Barcelona (Spain) | Building users<br>Researchers | Tomato | 3,4,5,6,7 |
| **Community rooftop garden** | Retrofit | Open-air | G2S<br>Grow to share | Soil-less<br>Hydroponic<br>Soil container | Via Gandusio, Bologna (Italy) | Social housing residents | Tomato<br>Lettuce<br>Eggplant<br>Chili pepper<br>Watermelon<br>Melon | 3,8 |
| **Private rooftop garden** | Retrofit | Open-air | G2P<br>Grow to produce (home use) | Soil-less | Gran Via, Barcelona (Spain) | Residents (1 family) | Tomato<br>Lettuce<br>Spinach | 3,9 |

***Figure 2.8.*** *Characteristics and specifications of the three case studies.*

## *2.2.1. Rooftop greenhouse: the RTG-Lab*

The Rooftop Greenhouse Lab (RTG-Lab) is the first documented rooftop greenhouse for food production in the South-West of Europe. The selection as a case study was based on the availability of real data on the construction phases, the accessibility to the architects and designers, the proximity and the uniqueness of the case study.

The RTG-Lab was constructed in 2014 on the top of the new building that hosts the Institute of Environmental Science and Technology (ICTA) and Catalan Institute of Palaeontology (ICP). The building was built in the campus of the Universitat Autònoma of Barcelona (UAB) (Bellaterra, Barcelona) and has a total area of 7,500 $m^2$ distributed in six floors. The ICTA-ICP building is a sustainable building that achieved the LEED-Gold® certification based on the principles applied in the design: energy efficiency, passive systems, compact volume, reversibility and multifunctionality, greenhouse and building-integrated agriculture (Figure 2.9a).

The RTG-Lab is a 125 $m^2$ greenhouse integrated in the building roof. The greenhouse structure is based on passive greenhouse technologies used in the south-Mediterranean horticulture industry. However, the conventional greenhouse structure was reinforced to comply with the legal framework: Spanish Technical Code of Edification (CTE) (RD 314/2006 (BOE 2006)) and fire safety laws (RD 2267/2004 (BOE 2004), Law 3/2010 (BOE 2010)). As a result, the RTG-Lab has a heavier and more resistant structure which is mostly made of steel, polycarbonate and polyethylene (Figure 2.9b). Soil-less cultivation is used as growing technique and research is focused on lettuce and tomato production (Figure 2.9c). Contrary to other RTG projects (e.g., Gotham greens), the RTG-Lab was included in the design of the building in a holistic way. As a result, the RTG-Lab is part of the upper floor of the building although this can be isolated through LDPE walls (Figure 2.9d).

***Figure 2.9.*** *The RTG-Lab: (a) the ICTA-ICP building in the UAB campus, (b) the greenhouse structure of the RTG-Lab, (c) Lettuce crop in December 2014, and (d) view of the RTG-Lab from the interior atrium of the rooftop.*

Beyond food production, the RTG-Lab aims to demonstrate the feasibility of integrated RTGs (i-RTGs) in Mediterranean areas. An i-RTG consists of a greenhouse that integrates its flows (energy, water, $CO_2$) in the metabolism of the building where it is placed on (Cerón-Palma et al. 2012). This approach is based on industrial ecology concepts and seeks an increase in the resources efficiency of both systems.

As a first experience, the RTG-Lab takes advantages of the metabolic flows from the building as follows (Figure 2.10):

- the residual air of the acclimatized offices and labs can be used in the greenhouse to heat or cool the space, improving the thermal conditions for crop production and minimizing plant mortality risk
- the residual $CO_2$ concentrated in the residual air from the building is also introduced in the greenhouse as carbon enrichment, boosting the biomass production of plants
- the building harvests rainwater in the roof, which is used for the irrigation requirements of the crops, leading to a 100% water self-sufficient production

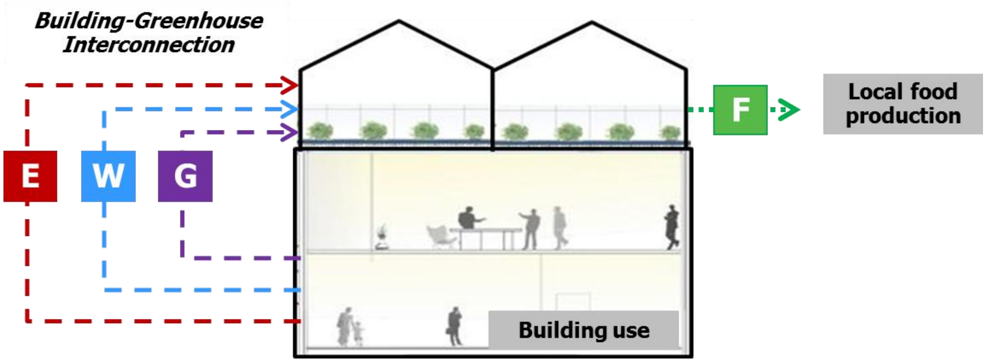


***Figure 2.10.*** *The i-RTG concept behind the RTG-Lab: the greenhouse uses residual flows (energy, gas) from the building and endogenous resources collected in the roof of the building (rainwater).*

Due to a lack of experimental data, the i-RTG concept was only used in a theoretical way in this dissertation. The potential increase of the crop yield (e.g., advantage of using the residual heat) was estimated and discussed in some of the chapters to highlight the potentialities of rooftop greenhouses when their flows are integrated.

### *2.2.2. Community rooftop garden: Via Gandusio*

Via Gandusio is a set of four social housing buildings situated in Bologna (Italy) that were constructed in the 70s. In its origin, this set of social housing was devoted to host poor Italian families, some of which still live in. However, the local government has recently changed the function of Via Gandusio to a provisional social housing while waiting for the definitive one. As a result, there is a high rate of people replacement that leads to a low sense of community. Furthermore, during the last years the presence of immigrant families has grown in Via Gandusio, worsening the situation (Marchetti 2012).

Within the *Green Housing* project, two community rooftop gardens were set up for addressing the social issues while greening the building and providing fresh produce to the residents. The project was a top-down experience with the participation of the local government, the agronomic department of the Università di Bologna and the non-profit organization BiodiverCity. The participation of these entities was essential for the development of the community garden as they supported economic costs, provided technical knowledge and worked on establishing a community group to maintain the garden through participatory events in the initial stage.

Nowadays, the community gardens are managed by residents of the building, which take advantage of the multiple functions provided by the community rooftop garden. Beyond food production, the garden is a new recreational space of the building that creates a meeting point for the residents to interact (see Figure 2.11a). Then, the garden acts as a source of community building and empowerment through a self-managed project. Furthermore, the users have worked on taking care of the space through art and decoration, leading to an improvement of the quality of this space.

The community rooftop garden uses different cultivation techniques which were all self-constructed (Do-It-Yourself, DIY):

- hydroponic floating production in containers, made of former pallets (DIY), which contains the nutrient solution to feed the plants (see Figure 2.11b)

- hydroponic production through Nutrient Film Technique (NFT) in PVC pipes along the walls of the rooftop
- soil production in containers, made of former pallets (DIY), distributed in the rooftop. Soil production is also performed in smaller DIY-spaces, such as decorative pallets (see Figure 2.11c)

**Figure 2.11.** *The community rooftop garden of Via Gandusio combines crops with recreational spaces (a), uses different cultivation techniques such as floating hydroponics (b) and is a Do-It-Yourself (DIY) garden (c).*

### *2.2.3. Private open-air rooftop garden: Gran Via*

As the third URF type, a private open-air rooftop garden was chosen due to the growing popularity of home-grown production that citizens perform in small spaces, such as balconies, terraces or rooftops. The Gran Via private rooftop garden was created in 2014 by the residents of the flat, which consists of a 2-member family. The garden is situated in the city centre of Barcelona, in the Eixample neighbourhood. The residential units of this neighbourhood are characterised by tall buildings that faces the street but that have internal courtyards, terraces or rooftops. The case study is the internal terrace of a 1st floor flat, that also acts as the rooftop of the lowest flat of the building (see Figure 2.12a). To reduce concepts mix-up, the space is named as a rooftop in the rest of the dissertation.

The private rooftop garden of the Gran Via is a 18m$^2$ crop space. The cultivation technique is soil-less production by employing perlite bags. The crop area is delimited with a wood structure that also included a waterproofed plastic soil (see Figure 2.12b). The garden is used year-round and crop diversity is high: 4 types of lettuce, tomato, zucchini, spinach, cabbage, peas and strawberries (see Figure 2.12c). Fertilizers are applied through the nutrient solution (i.e., automatic fertirrigation) and the production is pesticides-free (see Figure 2.12d).

***Figure 2.12.*** *The private open-air rooftop garden of Gran Via is placed in Eixample (a); a wooden structure (b) delimits the soil-less production area for multiple crops (c), which uses fertirrigation (d).*

The food production is aimed for self-supply of local vegetables and for sharing with the rest of the community. During this first year of activity, the rooftop garden drew the attention of the rest of the community, due to its noticeable situation, and most of neighbours were interested in visiting the garden and learning in detail the production process.

# Part II

## Assessment of urban rooftop farming implementation

# Chapter 3

## Resolving differing stakeholder perceptions of urban rooftop farming in Mediterranean cities

### Promoting food production as a driver for innovative forms of urban agriculture

Picture: *Community garden in the former Tempelhof airport (Berlin, Germany)*
*(©Esther Sanyé-Mengual)*

# Chapter 3

This chapter is based on the journal paper:

Sanyé-Mengual E, Anguelovski A, Oliver-Solà J, Montero JI, Rieradevall J (2015) Resolving differing stakeholder perceptions of urban rooftop farming in Mediterranean cities. Promoting food production as a driver for innovative forms of urban agriculture. *Agriculture and Human Values* (DOI: 10.1007/s10460-015-9594-y)

## Abstract

Urban agriculture (UA) is spreading within the Global North, largely for food production, ranging from household individual gardens to community gardens that boost neighbourhood regeneration. Additionally, UA is also being integrated into buildings, such as Urban Rooftop Farming (URF). Some URF experiences succeed in North America both as private and community initiatives. To date, little attention has been paid to how stakeholders perceive UA and URF in the Mediterranean or to the role of food production in these initiatives. This study examines the promotion and inclusion of new forms of UA through the practice of URF and contributes to the nascent literature on the stakeholder and public perceptions of UA. It seeks to understand how those perceptions shape the development of new urban agriculture practices and projects. Barcelona (Spain) was used as a Mediterranean case study where UA and URF projects are growing in popularity. Through semi-structured interviews with 25 core stakeholders, we show that UA is largely perceived as a social activity rather than a food production initiative, because the planning of urban gardens in Barcelona was traditionally done to achieve leisure and other social goals. However, several stakeholders highlighted the potential to increase urban fertility through URF by occupying currently unused spaces. As a result, the positive valuation of URF depends on the conceptualization of UA as a social or food production activity. In turn, such conceptualization shapes barriers and opportunities for the development of URF. While most UA-related stakeholders (e.g., food co-ops, NGOs) preferred soil-based UA, newer stakeholders (e.g., architects) highlighted the economic, social and environmental opportunities of local and efficient food production through innovative URF.

Keywords: Rooftop farming · Rooftop greenhouses · Urban self-sufficiency · Local production

## 3.1. Introduction

Urban agriculture (UA) experiences have spread over recent decades in cities in the Global North (Howe and Wheeler 1999; McClintock 2010; Smith et al. 2013; Mok et al. 2013). Consequently, sustainable urban production has become a growing field of interest among academics and professionals (Caplow 2009). UA has even become an extensive land use type in some cities. For instance, in Chicago (USA), a total area of 26.5 ha is devoted to food production in both residential (45.1%) and other types of urban gardens (e.g., community gardens) (Taylor and Lovell 2012).

Traditionally, the most important growth in Urban Agriculture has occurred during times of exceptional crises, such as during food shortages and wars (McClintock 2010; Mok et al. 2013). In North America and Western Europe, *War gardens* (WWI) and *Victory gardens* (WWII) fed people during the war periods with fruit, vegetables, and herbs that citizens planted at private residences and parks across the country. *Relief gardens* were an important contributor to food production during the Great Depression (Bassett 1981). More recently, during the collapse of the socialist bloc between 1989 and 1993 (the Special Period), UA produced a large amount of fresh food in Cuba and still continues to feed a significant number of people in Havana (Altieri et al. 1999; Cruz and Medina 2003).

Recently, UA has increased as a response to the current economic crisis in the Global North, such as in North America (Carney 2011; Taylor and Taylor Lovell 2012). Vacant land and community spaces are being used for UA by activists, community members, non-profit organizations, and local governments to increase food production in cities (McClintock et al. 2013). This trend emerged from the reshaping of urban development and land use by the financial and housing crises, with foreclosures and vacant properties opening up new spaces in cities and increasing food production opportunities (McClintock 2010). Additionally, UA activities respond to limited access to healthy food during economic crisis (Carney 2011). As a result, potential local production in the vacant lands of cities such as Oakland (California) represent as much as 30% of the city's food demand (McClintock et al. 2013). Other cities, such as Detroit, demonstrate the increasing reuse of abandoned urban land for producing food through both community-based initiatives and larger entrepreneurial investments (Dewar and Linn 2014).

In this sense, the primary goal of UA is often the production of food as a tool for achieving urban food security (Carney 2011) and promoting local production (Mok et al. 2013). At the community level, UA has played an important role in low-income communities and "food deserts" where access to food is limited, and UA has been used as a tool towards food justice (Guy et al. 2004; Wrigley et al. 2004; Smoyer-Tomic et al. 2006; Beaulac et al. 2009; Alkon and Agyeman 2011; Block et al. 2011; Carney 2011; McClintock 2011; Tornaghi 2014). At the individual level, growing food has also contributed to food security, improved health, local production, sustainable farming, and urban self-sufficiency (Kortright and Wakefield 2010). In particular, UA has been part of a growing demand for local products that also aims to re-connect consumers with the producers (Steel 2008). Urban food production also has numerous environmental benefits, such as reducing food transportation distances, improving waste recycling, optimizing food waste, and enhancing urban biodiversity (Howe and Wheeler 1999; McClintock 2010; Arosemena 2012; Guitart et al. 2012; Sanyé-Mengual et al. 2013; Smith et al. 2013).

In response to the growth of UA, decision makers have included UA in planning and policy regulations and local ordinances about land use. For instance, in December 2013, the Boston Zoning Board approved urban farming guidelines that legalize and regulate urban agriculture in the city. In 2010, Chicago published the *GO TO 2040* regional plan to enhance sustainable policies in the metropolitan area. Local food production has an important role in the *GO TO 2040* plan, where local food is promoted by means of supporting urban agriculture, expanding farmland protection and increasing community access to fresh food (Chicago Metropolitan Agency for Planning 2010). At the national level, UA has also become an essential part of food policy in some countries where local food production is meant to be implemented on a large scale (Mok et al. 2013) and where UA-related funding programs have been promoted to support the agricultural endeavours of local producers (Taylor and Taylor Lovell 2012). Furthermore, UA is also rising as a response to the inclusion of food and climate change issues into local political agendas (Tornaghi 2014) and to the development of a food planning agenda from the national to the municipal level (Morgan 2009; Morgan and Sonnino 2010).

Finally, local UA food production is increasingly being seen as a tool for achieving urban food sovereignty (Carney 2011; Kirwan and Maye 2012), which is defined as the community's right to define its own food and agricultural systems (Via Campesina 2002). UA activities are often related to the creation of alternative food value chains to the global market (Block et al. 2008) and a de-linking of food production from the current industrial food system (Wekerle 2004). As a result, some local food systems are sometimes developed as an alternative to the global agri-business market, which is largely comprised of multinational grain traders, giant seed, chemical and fertilizer corporations, and global supermarket chains (DuPuis et al. 2011).

Additionally, recent studies have examined the social benefits of UA, which have often become the main motivation for the promotion of UA initiatives. Commonly, socially oriented UA is created at the community level and in the form of community gardens. The social values associated with UA are community empowerment, health improvement, social organization, social cohesion, social inclusion, and education (Howe and Wheeler 1999; Armstrong 2000; Lyson 2004; Lawson 2005; Teig et al. 2009; Carney 2011; Block et al. 2011; Guitart et al. 2012). Gardens also have healing properties at the individual level and can help participants recover from traumatic experiences (Marcus and Barnes 1999; Gerlach-Spriggs et al. 2004).

### *3.1.1. Urban Rooftop Farming (URF)*

The progressive inclusion of UA in cities has given rise to multiple forms and locations of urban food production in the urban space: from traditional sites, such as community farms, community gardens, backyard farming, and vacant lands to site situated in and on buildings (Cohen et al. 2012; Specht et al. 2014). The use of building spaces for UA has been conceptualized in the literature in different ways: Vertical Farming (Despommier 2011), Zero-acreage Farming (Specht et al. 2014), Building Integrated Agriculture (BIA) (Caplow 2009) and Skyfarming (Germer et al. 2011). Nevertheless, building-based UA forms are numerous ranging from indoor farming by means of high-tech systems to open-air rooftop farming with hand-made pots.

In this paper, we focus on Rooftop Farming (open-air) (RF) and Rooftop Greenhouses (protected) (RTGs), which all come under the umbrella term "Urban Rooftop Farming" (URF) (Figure 1). Both systems are placed on rooftops and devoted to horticulture through different technologies. RF is an open-air system that usually consists of soil cultivation techniques, although soil-less techniques can also be used for specific plants (e.g., hydroponic growing for lettuce). RTG is a protected horticulture system based on the use of a greenhouse structure, and it is mainly implemented through soil-less growing systems (e.g., substrate) (Cerón-Palma et al. 2012). As a result, there are notable differences between the two systems. On the one hand, RF is commonly cheaper than RTG to implement, although the management of structural loads and water is more complex. On the other hand, RTG yields greater productivity because the climate is controlled, and soil-less systems increase resource use efficiency. However, the expense and complexity of soil-less techniques often render them unattractive options for non-commercial agricultural endeavours.

URF systems have been implemented in North America and Europe. Rooftop Farming (RF) is used both in non-commercial and commercial activities, such as in “Food from the sky” (London, UK) (Local action on Food 2012) and Brooklyn Grange[15] (New York, USA). RTG projects are mostly concentrated in North America and are run by local production companies. As an example, Gotham Greens[16] (Brooklyn, NY) has been producing greens in a 1,400 m$^2$ RTG since 2011, and Lufa Farms[17] (Montreal) cultivates greens and different varieties of tomatoes, cucumbers, peppers, and eggplants in a 2,900 m$^2$ RTG.

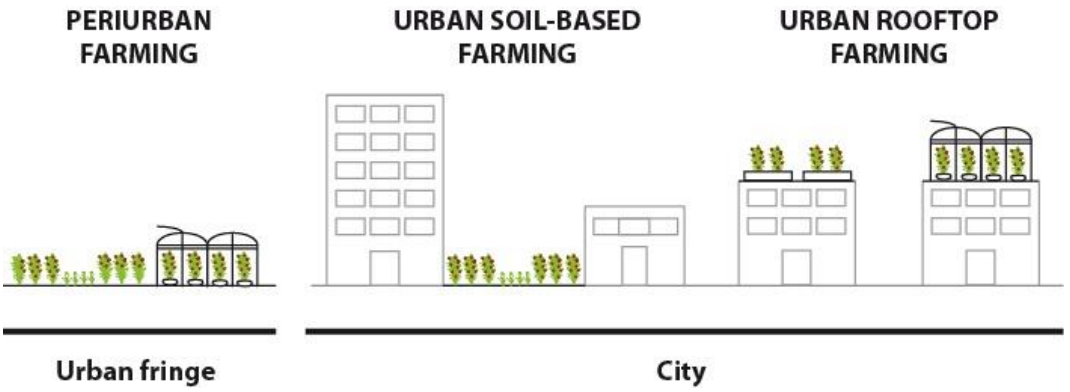


***Figure 3.1.*** *Forms of periurban (situated in the urban fringe) and urban farming (placed in the city). Urban Rooftop Farming can take form of Rooftop Farming (left) or Rooftop Greenhouse (right) (own elaboration).*

### *3.1.2. Research on Urban Rooftop Farming*

Literature around URF has dealt with the quantification of environmental and economic balances, agronomic aspects and the theoretical background. Attention has been paid to the potential implementation and contribution of URF to the domestic vegetable production (Astee and Kishnani 2010; Whittinghill et al. 2013; Orsini et al. 2014; Sanyé-Mengual et al. 2015a), the environmental savings of substituting imported products by local URF vegetables (Sanyé-Mengual et al. 2013), and the environmental and economic burdens of local production through Rooftop Greenhouses (Sanyé-Mengual et al. 2015b). Thomaier et al. (2014) reviewed current URF projects focusing on their sustainability aspects.

The barriers and opportunities related to URF have been also identified in the literature. Specht et al. (2014) performed a literature review on opportunities and limitations of building-based agriculture, which they conceptualize as Zero-Acreage Farming (ZFarming). They identified multiple positive impacts in the three pillars of sustainability (society, economy, environment), although only at the theoretical level. Cerón-Palma et al. (2012) paid attention to the barriers and opportunities associated to Rooftop Greenhouses that technical focus groups (e.g., architects, engineers) identified, thereby providing a comprehensive feasibility analysis. However, there is a

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[15] *http://brooklyngrangefarm.com/*
[16] *http://www.gothamgreen.com*
[17] *https://lufa.com/*

lack of studies around the perceptions of current and potential stakeholders involved in UA and URF projects.

### *3.1.3. Research objectives*

Despite nascent recent URF literature, little research has been conducted to analyze the potential role of URF in urban agriculture. To date, there is a lack of studies—particularly qualitative critical ones—analyzing the relationship of URF with Urban Agriculture from the point of view of the various public and private stakeholders involved in their development and of the perception-related, policy, and contextual constraints behind the development of URF. More research is needed to understand the relationship between the multiple roles played by urban agriculture, stakeholder perceptions of these roles, and the potential of further URF development.

To address these gaps, this paper explores the following research questions:

- How are UA and URF systems perceived in cities where UA has been growing and has been institutionalized?
- Is food production the main driver in the development of UA in such cities? Does URF promote food production in UA?
- What are the perceptions of implementing URF systems in those places? What types of barriers and opportunities are identified by the different stakeholders? How do these perceptions vary among different stakeholder groups?

In other words, this study examines the promotion and inclusion of new forms of urban agriculture through the practice of urban rooftop farming and contributes to the nascent literature on the stakeholder and public perceptions of urban agriculture. It seeks to understand how those perceptions shape the development of new urban agriculture practices and projects. We use qualitative research (semi-structured interviews) applied to a case study of a Mediterranean city—Barcelona (Spain)—with a growing and institutionalized presence of urban agriculture.

## 3.2. Research design

### *3.2.1. Case study selection*

The city of Barcelona (Catalonia, Spain) was chosen as a single-case case study (Yin 2008) based on the following criteria. First, Barcelona is a representative case of a Mediterranean city—conceived as a city with a welcoming climate for agricultural production—where both open-field rooftop farming and rooftop greenhouses can be easily implemented. Its sunny and hot climate offers a strong potential for the development of new agricultural practices and techniques such as URF. Rooftop greenhouses could also be useful in order to increase the production of summer crops, such as tomatoes, and offer a winter production without requiring an energetic input to heat the greenhouse, in contrast to European Atlantic or Continental cities. Second, urban agriculture in Barcelona is both developed and growing, and there is much public and private interest in increasing the role and place of urban agriculture in the city. Additionally, there is an increasing institutional and citizen awareness around UA, as well as political support from a variety of municipal programs, including local food coops and community gardens.

To date however, large-scale URF projects have not been planned even though URF can become a key strategy for promoting UA because Barcelona is a densely populated area with limited soil availability (as stated in Dubbeling [2011]) and because discussions on URF have been initiated at the pilot projects level, such as the research oriented RTG in the new ICTA-ICP building (Bellaterra, Barcelona). Moreover, local and ecological production is increasingly valued (Giacchè and Tóth 2013). For example, the metropolitan area of Barcelona consumes 75% of the production of the Baix Llobregat Agricultural Park (BLAP), which is a protected agriculture area of 2,700 ha situated 10 km to 15 km away from Barcelona city (Paül and McKenzie 2013). Moreover, the agricultural production area of Maresme, which represents 17% of total agricultural production in Catalunya (DARPMA 2012), is a source of local produce because it is situated only 30 km to 40 km away from the city. Finally, Barcelona is a focal point of the Southern European food market due to the activity of MercaBarna (food distribution centre).

### *3.2.2. UA stakeholders in Barcelona*

#### (i) Current trends and stakeholders involved in the development of urban agriculture in Barcelona

Our data collection reveals that large-scale urban agriculture (UA) in Barcelona is promoted by the municipal administration through the program *Barcelona Urban Gardens Network* (Xarxa d'Horts Urbans de Barcelona), which is managed by the municipal Department of Environment.[18] Within this program, three types of urban gardens have been developed: urban gardens, school gardens and supported community gardens. Prior to these projects, UA was limited to the development of individual gardens in occupied vacant lands in the outskirts of the city (Ajuntament de Barcelona 2014).

Official UA initiatives in Barcelona began in 1986 with the creation of the urban garden *Hort de l'Avi* (Old men's garden) as a response to the demands of elderly citizens in Barcelona (Giacchè and Tóth 2013). Today, there are 2.5 ha devoted to 13 urban gardens throughout the city. However, these plots are dedicated to a certain group of the population (>65 years old) and are awarded individually. That said, the last urban garden (2011) includes some plots for entities working with people at risk of social exclusion. In addition, the administration supports school and community gardens. Thus far, 315 school gardens have been created as educational urban gardens and as tools for implementing the Schools Agenda 21, which encourages schools to promote sustainable development locally (Ajuntament de Barcelona 2002). Finally, the city hosts community gardens supported by the administration that used to be squatting gardens. These gardens were accepted by the administration after citizens mobilized and implemented strong community building processes. For instance, *l'Hortet del Forat* in the Old Town began as a meeting point between residents who mobilized against the lack of public investment in their neighbourhoods and against land speculation (i.e., they began calling the meeting's square *El forat de la vergonya*—the hole of shame), and the garden eventually gained the support of the municipality (Anguelovski 2013).

Apart from the municipality-supported initiatives, other community and individual urban gardens were created during the last decade. "Squatting community gardens" are common. These gardens occupy unused empty spaces (e.g., empty space left after the demolition of an old building). Today, there are 43 squatting community gardens in Barcelona.[19] These gardens are usually managed by a group of young people who clean up the spaces to produce food but also to claim social space and improve the quality of life of the neighbourhood. However, these actions are not supported by the public administration, and squatters often encounter obstacles, such as fines

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[18] http://w110.bcn.cat/portal/site/MediAmbient/

[19] http://www.bcn.cat/agenda21/horts/index.htm

(Giacchè and Tóth 2013). Additionally, Barcelona has many individual urban gardens used as food production spaces in households (i.e., backyard, terrace, indoors).

Land in the urban areas of Barcelona is not commonly devoted to agricultural use beyond those formal urban agriculture initiatives. Land uses are defined in the municipality's zoning plans. In the case of Barcelona, the spatial planning policy has different levels: "Pla territorial metropolità de Barcelona" (PTMB) [Metropolitan regional plan of Barcelona] (Generalitat de Catalunya 2010), local "Pla Director Urbanístic" (PDU) [Local urban master plan] and "Pla d'Ordenació Urbanística Municipal" (POUM) [Municipal urban planning plan]. However, only in the PTMB is the land preserved as a natural resource (i.e., protected natural spaces) or as an agricultural space (i.e., agricultural parks). In contrast, in local zoning, land is preserved for future urbanization.

The economic crisis in Spain has severely affected the country's construction industry, which has in turn increased the amount of vacant land in Barcelona because many urbanization projects were cancelled. As a short-term response to the increase in public vacant land, in 2012 the municipality launched the PLA BUITS (Vacant Lands Plan) (Ajuntament de Barcelona 2012). The plan consists of a public offer of land to non-profit organizations with the aim of revitalizing vacant lands through community use. Nine of the 14 vacant pieces of land are now managed to create new community urban gardens (La Vanguardia 2013), accounting for an extra 0.7 ha of food production area in the city.

### (ii) Definition of the potential stakeholders involved in the implementation of URF

As a preliminary analysis, we identified the potential stakeholders involved in the implementation of URF in Barcelona city. This analysis focused on the different stages of the implementation of URF and their products (i.e., food products)—design, construction, production and consumption—because stakeholders are related to different stages. We also included potential promoters and opponents. The categories of stakeholders were chosen based on the key actors that the existing literature identifies in the urban agriculture and food planning community (Morgan 2009; Morgan and Sonnino 2010; Despommier 2011; Tornaghi 2014), on our knowledge of current UA and URF experiences in Barcelona, on snowball sampling with initial key stakeholders, and on the use of media information on existing stakeholders.

The resulting map of stakeholders (See Figure 2) combines all of the current stakeholders involved in urban agriculture (e.g., public administration, urban gardeners), the local production movements (e.g., consumers, food coops) (Giacchè and Tóth 2013) and the potential stakeholders related to the implementation of URF (e.g., architects, engineers, new producers). As part of our data collection process, we identified specific stakeholders within the same stakeholders' group who might have potential opposite perceptions. For instance, within the public administration, different offices can become supporters or opponents depending on whether they see URF as an opportunity for improving the environmental performance of products or as a problem due to, for instance, sanitary or economic factors. We also interviewed urban gardeners because of their important role in developing and promoting urban food production in Barcelona, as well as architects because of the importance of the legal and structural dimensions of using parts of buildings for food production.

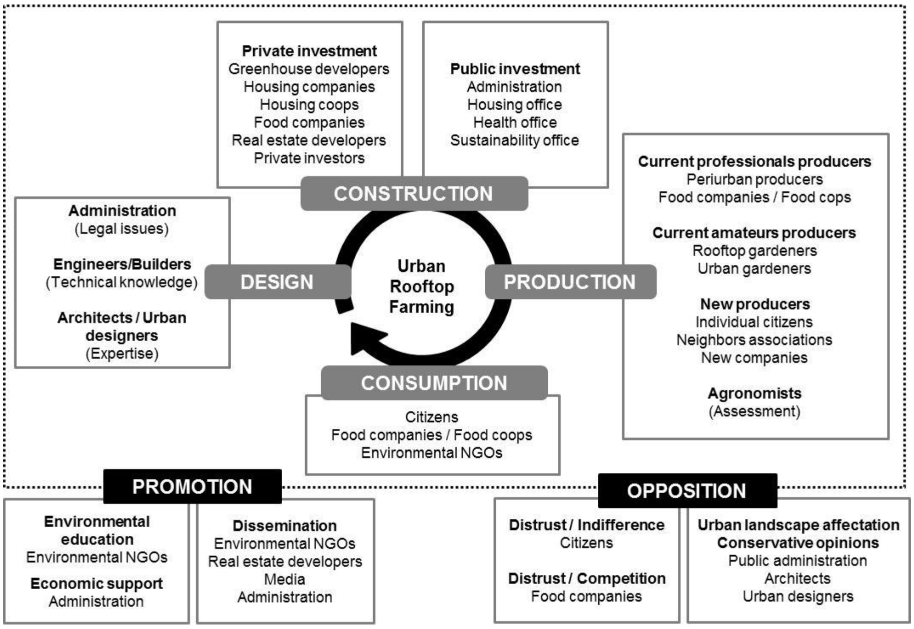

***Figure 3.2.*** *Map of stakeholders involved in the different stages of the potential implementation of Urban Rooftop Farming (own elaboration).*

### *3.2.2. Data and definitions*

#### (i) Data collection

We conducted semi-structured interviews with 25 participants during the course of this study. Participants represented the breadth of stakeholders' groups identified in the previous section and were chosen with the aim of understanding their experiences, points of views, and visions concerning four main topics related to URF: urban agriculture, sustainability, food systems, and urbanism and buildings. Much attention was paid to the potential implementation of URF systems, meaning that we looked closely at the opinions of the stakeholders within the city administration who could play an important future role in promoting URF (See Table 1).

Interviews were conducted from May 2013 to September 2013 and lasted from 30 minutes to 2 hours. We structured the interviews around three themes: agriculture and urban environment, urban agriculture, and urban rooftop farming. The first part explored the definitions of agriculture and urban agriculture as well as the agriculture-city relation. The second section of the interview was focused on discovering the involvement and perceptions of UA projects in the city of Barcelona. The third part was devoted to urban rooftop farming and to examining the knowledge, involvement and perceptions of the stakeholders in relation to the potential implementation of Rooftop Farming (RF) and Rooftop Greenhouses (RTGs) systems. In this last section, we paid special attention to the opportunities and barriers that stakeholders associate to URF. We analyzed the data through grounded theory methods (Corbin and Strauss 1990) where the transcripts and the field notes were open coded to identify key concepts and their relationships, and to avoid imposing pre-conceived theories on the data. This data collection and analysis was complemented by secondary data collection, including maps, reports, and press releases.

***Table 3.1.*** *Interview participants: stakeholders' group, stakeholders, number of respondents and main relation to urban rooftop farming.*

| **Stakeholders** | | | **Nº** | **Relation to URF** | | | |
|---|---|---|---|---|---|---|---|
| | | | | **UA** | **S** | **F** | **B** |
| ADMINISTRATION | | | | | | | |
| Regional | Generalitat de Catalunya (Government of Catalonia) | Department of Planning and Sustainability | 1 | | x | | |
| Local | Diputació de Barcelona (Barcelona Provincial Government) | Network of Cities for Sustainability | 1 | x | | | |
| | Ajuntament de Barcelona (Barcelona city council) | Economic promotion | 1 | | x | | |
| | | Municipal Institute of Parks and Gardens | 2 | | x | | |
| | | Municipal Institute of Urban Landscape | 1 | | | | x |
| | | Urban habitat | 2 | x | | | |
| | | Urban development agency | 1 | | | | x |
| UA-RELATED | | | | | | | |
| Local | Baix Llobregat Agricultural Park | Management | 2 | x | | | |
| | Urban gardens | Hort del Xino (El Raval) | 1 | x | | | |
| | | Hort de Fort Pienc | 1 | x | | | |
| | Squatting gardening | Can Masdeu | 1 | x | | | |
| | NGOs | Ecologistas en acción | 1 | | | x | |
| | Coop's users | Panxa contenta (Sants) | 1 | | | x | |
| ARCHITECTS | | | | | | | |
| Regional | Association of Architects of Catalonia | | 1 | | | | x |
| Local | Universitat Politècnica de Catalunya · BarcelonaTech | | 3 | | | | x |
| | Architects involved in RTG projects | | 1 | | | | X |
| PLANNING LAWYER | | | | | | | |
| Regional | Planning lawyer, with expertise in UA | | 1 | | | | x |
| FOOD DISTRIBUTORS | | | | | | | |
| Local | MercaBarna | Director of Facilities and Services | 1 | | | x | |
| OTHERS | | | | | | | |
| Local | RTG promoter (restaurant's owner) | | 1 | | | x | |
| | Green spaces' company (manager) | 1 | x | | | | |
| **TOTAL** | | | **25** | **9** | **4** | **4** | **8** |

*The current expertise and involvement in URF in Barcelona of interview subjects is specified as follows: urban agriculture [UA], sustainability [S], food systems [F], and urbanism and buildings [B]. Totals derived from cells indicated with "x" and number of interviewees.*

### (ii) Definitions of key concepts

In this section, we define the concepts related to agriculture and food that we use in our qualitative analysis. During the study, we differentiate between agriculture and horticulture to specify the production type. Horticulture is a branch of the agricultural sector that includes the production of vine fruits, vegetables, nuts, aromatic and medicinal plants, and ornamental and landscaping plants, as defined by International Society of Horticultural Science. Second, the location of the agricultural activity is used to differentiate three types of agriculture in the analysis:

- Urban agriculture refers to agricultural activities performed within the city limits
- Periurban agriculture is defined as agricultural activities performed in the urban fringe, outside the city limits.
- Rural agriculture refers to agricultural activities not performed in urban areas, neither inside nor the fringe.

In regard to food concepts, food security (Carney 2011) refers to the access of citizens to healthy food, in quantitative terms (i.e., amount of food). By contrast, food insecurity is used when stakeholders lack of access to an amount of food that can satisfy their needs. The right to healthy, fresh, local, and affordable food for community food security has been at the centre of community advocacy for food justice (Via Campesina 2002; Hess 2009; Gottlieb and Joshi 2010; Alkon and Mares 2012). Food safety considers the quality of food, in qualitative terms (i.e., freshness, health). Food sovereignty includes the access to food and production resources (e.g., including land access, economic resources), in social and political terms. It refers to the capacity of individuals and groups to control their access to food and define their own food systems(Via Campesina 2002; Alkon and Agyeman 2011).

Finally, the analysis focuses on perceptions, conceptualizations, and drivers. Perceptions include the opinions, stories, and experiences of stakeholders (e.g., identification of opportunities). Conceptualizations are the specific definitions that stakeholders link to different elements and systems (e.g., defining agriculture). Drivers are the motivations behind decisions, thereby include the main objectives of projects (e.g., addressing social exclusion).

## 3.3. Data analysis: the potentials, opportunities, and constraints of expanding urban agriculture in Barcelona

In this section, we show that the acceptance of URF and its potentialities in Barcelona mostly relies on shifting the driver of UA from social values to food production itself, or at least on bringing the social goals of UA with its food production potentialities together closely.

### *3.3.1. Differing perceptions and definitions of urban agriculture in contrast to experiences on the ground*

In this section, we examine how UA and URF systems are perceived in Barcelona. Through our analysis, we found three main trends on how stakeholders conceptualize UA and how this conceptualization affects the perception of URF (see Figure 3). First, periurban stakeholders do not include UA in their definition of a real agriculture, producing a conceptual barrier for supporting any kind of UA activity. Second, among those stakeholders, those that define UA as a real agriculture, the purpose of the activity becomes the defining factor for supporting different types of projects. On the one hand, some urban stakeholders (i.e., urban gardeners, administration, NGOs, food coops, food managers) only conceptualize UA as a socially oriented activity. In those cases, they do not support URF because the initial investment required for the activity is perceived as too high. Within this group, stakeholders who focus their attention on local production (i.e., NGOs and coops) value the food production function of periurban agriculture but only perceive the social functions of urban agriculture. On the other hand, when stakeholders (i.e., urban gardeners, regional administration, architects) value UA as a food production system, they usually accept the development of RTGs as yields are increased, thereby valuing the potential environmental, social, and economic benefits tied to local production within the city. This social-production conflict is further discussed.

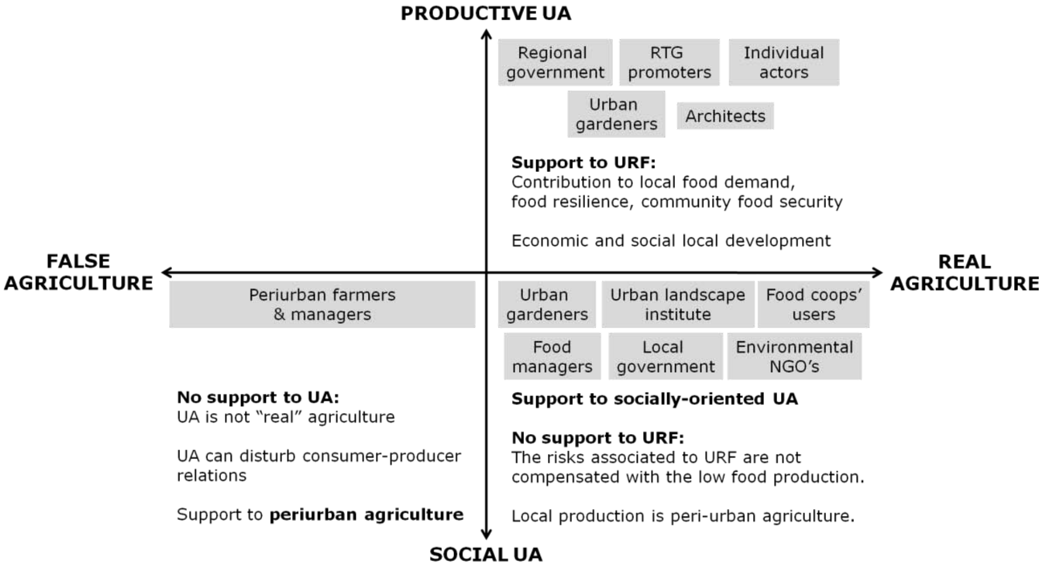

***Figure 3.3.*** *Stakeholders' position on conceptualizing UA.*

Among the interviewed stakeholders, UA is not universally perceived as "real agriculture," which some stakeholders define as an activity that can only be located on agricultural land and performed by professional farmers (i.e., people trained for agricultural activities that perform a paid labour). This lack of consistency when defining agriculture acts as a barrier to implementing both UA and URF in Barcelona. Such a reality is reflected in the words of some professional stakeholders involved in periurban agriculture:

> *There are no professional farmers and Urban Agriculture is not developed on agricultural land [...] Understanding that you can feed the citizen through UA is uncertain. There is a risk of confusion... It can be complementary but in the city it cannot be considered as agriculture [...] and it wouldn't be agriculture, which also conserves the territory and has other functions [...] Agriculture is also landscape (Managers of the Baix Llobregat Agricultural Park, BLAP).*

The different conceptualizations of Urban Agriculture in Barcelona are built on what stakeholders see as a weak and distant relationship between agriculture and cities. There is a lack of current and real integration of agriculture in the city resulting from the long expulsion of agriculture from Barcelona due to industrialization and urban development. Additionally, many production spaces were converted into urban parks and land speculation areas. The following stakeholders describe clearly the disconnection between agriculture and the recent history of Barcelona:

> *The current relation is distant. We don't realize the importance of rural areas and how the city needs them [...] We are out of place, and we have little knowledge about farming (Urban garden user).*
>
> *Cities have turned their back to agriculture (Environmental NGO based in Barcelona).*
>
> *The relation city-agriculture is completely opposed [...] Rural area or agriculture (as opposite to city) is defined in economic terms as an area for which the price is based on the*

> *capitalization of the agricultural activity. However, prior to industrialization, the relation was different. Agriculture was integrated in cities through backyards, gardens (Architect).*

On the ground, however, the spread of UA in and around Barcelona has become an emerging economic activity. For instance, in Cardedeu (Barcelona province), *L'hort d'Esbiofera* offers training courses for urban gardeners, and the community garden *Phoenicurus* commercializes its produce through a local cooperative (EU'GO Project 2014). In other countries, such as in North America, UA has generated a new sector of local production that has created green jobs (i.e., new professional urban farmers) in URF and community farming businesses (e.g., the abovementioned Gotham Greens, Lufa Farm and Brooklyn Grange). UA in Barcelona is on a similar path to developing a green economy.

Moreover, UA in Barcelona has an important effect on the urban landscape by greening urban areas and buildings. For example, the initiative "Recreant Cruïlles" has turned an abandoned plot of land (abandoned due to the non-execution of public projects) into a community space with gardens while improving the plot's aesthetics and bringing green space into the neighbourhood (which currently only has 1.37 square meters of green space per inhabitant).[20] Thus, some characteristics of UA in Barcelona may match the definition of "real agriculture" defined by some of the stakeholders. Therefore, there is a need to revisit the concepts around periurban agriculture and UA to include the reality of UA in their definitions. Even more, the definitions of UA may be geographically contextualized and may vary depending on the multiple forms that UA can take.

### *3.3.2. The difficulty of making URF as a municipal priority*

#### (i) A much needed shift from social benefits to food production in UA

Our interviews revealed that the stakeholders most closely affected by current UA initiatives (i.e., administration, urban gardeners, NGOs, coops) are largely concerned with the social values of such initiatives and therefore perceived UA more as a socially oriented activity and as a practice with healing and therapeutic goals for traditionally vulnerable groups in the city. Most UA-related stakeholders identified leisure and self-sufficiency as the drivers for current public and private horticultural experiences in Barcelona. Specifically, education is the main motivation for school gardens, where children learn earth sciences and farming and cooking skills. Additionally, therapeutic goals were also identified from working with people with disabilities. Current institutionalized forms of UA initiatives (e.g., Vacant Lands' Plan) also focus more on this therapeutic value and on social inclusion activities by including local and social organizations in the development of UA projects. This perception of UA originates in the fact that the first UA actions in Barcelona were geared toward addressing social needs (i.e., urban gardens for retired people). The promoter of urban gardens in Barcelona described the origin of urban gardens as follows:

> *Urban gardens are pieces of land (30–100–150 m$^2$) assigned by the City Council for five years. The approach is a leisure form of UA initially designed for old people. The idea was to improve their health by providing an open-air space for a hobby [...] This is a social initiative rather than an economic one [...] So, they are dedicated to families and contribute to their self-sufficiency (Promoter of urban gardens in Barcelona).*

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[20] http://recreantcruilles.wordpress.com/

In such a vision, the food production function is eclipsed by the potential social benefits of current UA activities. Therefore, although URF attempts to increase the fertile area and the associated food productivity of cities, many stakeholders in Barcelona perceive URF as a complex system with costs and obstacles largely superior to the potential benefits. Furthermore, although some stakeholders (i.e., coop users, urban gardeners, environmental NGOs) consider positively the use of rooftops for horticulture, they do not accept the use of soil-less techniques for increasing crop yields because such techniques are perceived as a non-sense option: RTGs are unnatural, detached from the land, provide low quality products, and require the use of an expensive technology. As a representative from the Network of Cities for Sustainability explains:

> *The needed infrastructure… and the soil-less techniques… RTGs are related to an important investment that doesn't seem feasible unless driven by a private company. Then, if the social part is only complementary, the activity is not so interesting […] A piece of land is cheap; you give it to them, labour is free… An RTG is not so cheap. In the long-term, it is more productive and makes sense, but not for a social activity (Network of Cities for Sustainability).*

Beyond the perception of URF, the desired spatial distribution of food production in the city depends on the public's conception of UA. Some stakeholders who support local food promotion do not identify the city as a potential production area because UA is perceived as socially oriented agriculture. Urban gardeners, food coops and NGOs thus only see periurban farming as a source of local "urban" produce. These stakeholders commonly promote periurban farming and social initiatives in UA but pay little attention to UA projects focused on food production. This perception is also linked to the specific urban morphology of Barcelona, which is a small and compact city compared to other metropolises. For instance, the respondent from the Urban Development Agency of Barcelona valued the great potential of large industrial roofs in cities such as New York, but not in Barcelona where industries where displaced to the outskirts and replaced with residential and services buildings:

> *In New York, industrial buildings [that were initially placed in the urban fringe] were progressively absorbed by the city. Then, within the urban fabric there are buildings with large and resistant roofs that can be reconverted into urban gardens, rooftop gardens or even rooftop greenhouses, thereby being in direct contact with citizens and consumer" (Urban Development Agency of Barcelona).*

However, when stakeholders identify food production as the main function of UA, URF is positively valued as a driver behind urban food security. A few of the UA-related stakeholders, such as some urban gardeners, consider URF as a potential change towards a more productive UA. New stakeholders involved in URF (e.g., architects) establish food production as the main motivation for promoting UA and, consequently, positively consider URF and RTG as new UA forms. The technical solutions offering higher yields (soil-less systems) and longer crop periods through the use of greenhouses have increased interest in UFR and RTG. Therefore, URF can reshape how UA is being used and promoted in Barcelona and can transform the city into a more productive place that promotes UA to alleviate food insecurity while taking advantage of the resultant social benefits, as an urban garden user emphasizes:

> *I think that URF can be a very useful way towards initiatives for food production that aim at closing cycles. There have been enough community activities for social and educational purposes and, maybe, it is time to change to a real productive UA (Urban garden user).*

### (ii) The potential of enhancing food production through local urban sustainability policy

This social versus production dichotomy within UA plays an important role in the inclusion of local food production in the development and implementation of urban sustainability policies in Barcelona. At the regional level within Catalonia, existing sustainability programs include different aspects that can be related to URF as they seek, among others, the optimization of energy resources, the increase of local production and the development of a green economy, as outlined by the Department of Territory and Sustainability of the Government of Catalonia:

> *Among the sustainability policies, there are different aspects where URF fits. Broadly, the Catalan Strategy for Sustainable Development includes climate change mitigation, water, chemical products, GMOs, the green economy and the creation of green jobs. Therefore, URF could be an innovative activity for generating green jobs without increasing environmental impacts (Government of Catalonia).*

Moreover, as indicated by the local administration, self-sufficiency is one of the key aspects within the 2050 Roadmap, not only at the energy level but also for reducing consumption by becoming more efficient. Thus, stakeholders identified the minimization of transportation distances through local production as an important value to consider in future urban sustainability policies. However, this opinion contrasts with the perception of other members of the local administration who perceive local production as an unimportant target, such as staff members from the Office of Economic Promotion who centre their attention on sustainable mobility. That said, both areas (urban habitat, economic promotion) have in mind similar goals for local policymaking: economic potential and climate change mitigation.

Furthermore, at the local level, although UA fits well with plans, policies, and discourses, it is still perceived as a complicated scheme for implementing on a large scale. UA matches new planning trends in Barcelona that aim at converting vacant lands or green parks into urban gardens. UA and URF are in line with the discourse that cities must be fertile again. Beyond food production, RTG responds to the need to improve the energetic performance of buildings through the interconnection of flows between the building and the greenhouse matching the energy programs of the Barcelona government, as stated by an urban planning lawyer.

However, local decision makers outline several technical and financial constraints when they discuss the potential of URF, particularly RTGs. When compared to current soil-based UA projects, URF requires a higher technology level (e.g., hydroponics, greenhouses, rooftop adaptation). The related complexity and economic cost is the most critical aspect of URF. Since the driver in official UA projects is social rather than productive, these aspects are not balanced with the potential local food production from URF. A member of the Barcelona City Council explains:

> *URF is complex (e.g., rooftop's property) and requires an investment that the city cannot face in the current economic context, although it perfectly fits with the sustainability discourse […] There are several benefits, but the cost is too high […] Currently, we are promoting UA in vacant lands, where the public cost is only the adaptation of the land for the activity, and such activities are promoted for social activities, for local organizations […] Regarding jobs and food production, the local administration is planning a project for social companies, which only aims at job creation for disabled people (Urban habitat, Barcelona city council).*

In other words, although food production and its opportunities (e.g., self-sufficiency) can be inserted within urban sustainability policies, the potential of systems oriented toward food production (e.g., RTG) is not considered as a feasible alternative for the near future. The way in which most stakeholders in charge of decision making conceptualize UA—as a socially oriented activity—negatively affects the creation of new UA systems designed to increase productivity in urban areas.

### (iii) Developing URF for food sovereignty through an alternative and equitable use model

Because URFs have yet to be implemented in Barcelona, stakeholders discussed three main use models for them: commercial use (private company), self-sufficiency use in public buildings (both community and single), and self-sufficiency use in residential buildings (both community and single). These models are important in influencing how stakeholders perceive URF because some stakeholders do conceptualize UA as a potential local food model. They seek a use model that is equitable and supports food sovereignty in Barcelona. Therefore, the ideal use model would be a self-sufficiency, community-based URF that would be independent from global markets and could take place in public buildings and in new social housing. It also would help socially fragile communities achieve greater food sovereignty since they would have control over how and where their food is consumed. For instance, food would be produced on the rooftop of social housing buildings, with the possibility of paid labour for residents and of food consumption by the residents themselves:

> *The commercial is not interesting… We want to close the cycles. If I produce the food in my rooftop, it should be for my consumption (Coop user).*
>
> *Social housing [would be envisioned] beyond a low-cost rental, where also electricity and water costs can be low, and self-consumption and self-production can be included [through URF]. Then, self-sufficiency would be promoted (Network of Cities for Sustainability).*

Thus, there is a group of stakeholders from the administration, food coops, and groups involved in UA activities (e.g., urban gardeners) that want to address social disparities and create a food production system accessible to everyone by using UA and URF as tools against capitalism and the power of agribusiness. These stakeholders support URF based on various factors, such as accessibility and users' decision making power. Their vision is meant to ensure an alternative model that guarantees the fulfilment of a basic need (i.e., food) under terms decided by community members and users. They insist on the need for a URF that exists outside the capitalist system, which concentrates production in the hands of a minority while negatively affecting the environment, the economy, and society.

### *3.3.3. Current barriers to and opportunities for URF: coupling sustainable local production with technological complexity*

Respondents reported different barriers and opportunities regarding the future implementation of URF systems. All of the respondents identified environmental, economic, and social opportunities that would positively contribute to urban sustainability. However, they also identified some barriers, particularly those regarding legal and technical constraints. A summary of barriers and opportunities is offered in Table 2.

The results varied between different stakeholders' groups, although all of them identified environmental and social opportunities. Most of the stakeholders from the administration supported RF but not RTG due to economic, legal, and technical barriers. However, some offices did positively value RTGs due to their potential to develop a green economy and the potential optimization of a closed-flows system. UA-related stakeholders also observed environmental and social benefits because they pursue socially oriented URFs rather than commercial initiatives. However, stakeholders also noted economic barriers and potential social constraints, such as accessibility. Despite this general trend, a couple of UA-related stakeholders underlined the great opportunity of RTGs to increase food production in cities and the resultant environmental, social, and economic opportunities. Architects had a common opinion on RTGs and mentioned the potential opportunity to exchange metabolic flows between greenhouses and buildings. Architects identified technical and legal barriers but considered them easy to overcome with the support of the administration. Stakeholders that promote RTGs underlined business benefits while pointing out current legal barriers, such as administrative permits for rooftop usage and for greenhouse implementation. The food distribution company found RTG a positive system in environmental and social terms but expressed doubts about its economic feasibility. Finally, the manager of a green spaces company noted logistics and management as important barriers but positively valued RTGs not only for horticulture but also for gardening and value-added products (e.g., dried tomatoes).

***Table 3.2.*** *Barriers and opportunities around Rooftop Farming (RF) and Rooftop Greenhouses (RTG), and comparison with previous studies on URF.*

| | **Stakeholders** | | **Cerón-Palma et al. (2012)** | **Specht et al. (2013)** |
|---|---|---|---|---|
| | **RF** | **RTG** | | |
| Environmental opportunities | | | | |
| Reducing pressure on fertile soil | x | x | x | x |
| Reducing food miles and transport emissions | x | x | x | x |
| Using and recycling water resources | x | x | x | x |
| Optimizing energy consumption | x | x | x | x |
| Carbon & contamination fixation | x | x | x | |
| Naturalization of the city | x | x | x | |
| Recycling organic waste | x | | | x |
| Sustainable architecture and urban landscape | | | | x |
| Increased habitability of the building | x | x | | |
| Increase of horticulture yields | | x | | |
| Enhancing closed cycles | x | x | | |
| Environmental barriers | | | | |
| Perception of little environmental benefits | | x | | x |
| Limitations to recycle organic matter in nutrient solutions for hydroponic systems | | x | | x |
| Environmental impact of construction materials | | | x | |
| Competition with solar energy | | | x | |
| Technical barriers | | | | |
| Integration in existing buildings | x | x | x | x |
| Building overloading and need of reinforcement | x | x | x | |
| Risk of contamination (air pollution) | x | x | | x |
| Logistic constraints in urban areas | x | x | | |
| Crop management limitations | x | x | | |
| Legal barriers for rooftop usage | x | x | | |
| Social opportunities | | | | |
| Improving community food security | x | x | x | x |
| Providing education on food production | x | x | x | x |
| Value of fresh produce | x | x | x | |
| Linking consumers to food production | x | x | | x |
| Community building and empowerment | x | x | | |
| Increasing consumers' awareness | x | x | | |
| Social barriers | | | | |
| Need to train qualified personnel | x | x | x | |
| Lack of acceptance of soil-less growing techniques | | x | | x |
| Social disparities in access to systems and products | | x | | x |
| User's acceptance | x | x | | |
| Management barriers | x | x | | |
| Economic opportunities | | | | |
| Reduction of costs (transport, resources use) | x | x | x | |
| Revaluation of unproductive spaces | x | x | x | |
| Local development | x | x | | x |
| Potential products and high yields | x | x | | x |
| RSC and corporate image | x | x | | |
| Economic barriers | | | | |
| Competition to other uses | x | x | x | x |
| Investment costs (i.e., infrastructure) | x | x | x | x |
| Narrow profit margin for horticultural products | | x | x | |
| Consumers' acceptance | x | x | | |
| Exclusion of certain crops (e.g., no cereals) | | | | x |

### (i) Environmental aspects

Beyond the usual environmental opportunities offered by local food production, such as the reduction of pressure on fertile soil and of food miles, stakeholders underline new environmental benefits at the urban scale and at the building scale. First, URF can improve the air quality of urban areas by sequestering carbon and other contaminants. Moreover, URF promotes the greening of urban landscapes. However, both benefits are more associated with RF than with RTG because RF is an open-air activity. Second, there are opportunities for potential energy savings due to improved building insulation. Finally, the environmental benefits associated with horticultural production are related to the optimization of water consumption and the potential recycling of organic waste. One of the most interesting opportunities observed by the stakeholders is the potential increase of crop yields due to urban air contamination:

> *Here [in MercaBarna] we have a treatment plant [for the food waste], which generates an important amount of air emissions… At this green point, we have a green barrier where plants grow much because of the substances in the air (such as carbon dioxide emitted during natural fermentation) (MercaBarna).*

Both systems (RF and RTG) can benefit from this urban fertilization, although RTG can achieve higher yields by closing the cycles with the building (e.g., residual $CO_2$). For instance, architects highlight the potential reduction of $CO_2$ emissions through the recirculation of residual $CO_2$ from the building to the greenhouse and the reduction in energy consumption, which also generates cost savings. In this sense, URF systems respond to the need for more productive and sustainable urban food systems. The resultant synergies are of great interest not only for horticultural production but also for the building itself:

> *Soon, buildings will have to achieve zero-consumption and, within this, we should add a certain productivity to the own building. The water cycle has been deeply studied, such as rainwater harvesting for non-potable uses. We need to close the flows. The more we close the cycles of a building, the better environmental profile it has: less energy, less material, less water, fewer imports (Generalitat de Catalunya).*

Stakeholders identified few environmental barriers. Environmental opportunities and potential impact savings of local production were mentioned by all of the respondents as the most common opportunity of UA. Barriers were mostly related to the organic waste management of the horticultural production system, which cannot be used as fertilizer in soil-less systems (RTG). Some of the stakeholders noted that a local food system should guarantee that the organic waste generated can be absorbed by the city.

### (ii) Technical aspects

Respondents identified various technical constraints for implementing URF. The inclusion of agriculture in cities shows some logistical barriers regarding the transportation of inputs and outputs (resources, produce, and generated waste). In regards to crop management, the use of chemicals (fertilizers, pesticides) for food production may be restricted due to safety regulations. Several other technical barriers include water management, structural loads, integration on existing buildings, and the risk of contamination due to air pollution. Some stakeholders noted that the use of greenhouses in RTGs is unnecessary for the climate conditions in Barcelona. Finally, the Municipal Institute of Urban Landscape does not support greenhouses because they disrupt the visual image of the city. Some stakeholders describe these barriers as follows:

> *Is the inversion worthy? Rooftop farming needs a larger economic investment for reinforcing the rooftop, the infrastructure, and even more, when considering a greenhouse production…*

> *Soil-based urban agriculture is cheaper… You just need to prepare the soil. (Local administration)*
>
> *There are some technical barriers that need to be addressed in URF projects. The structural loads… we need to check resistance or reinforce the rooftop […] The water management can be also a technical barrier if we need to storage it… more load. (Architect)*

The current legislation in Catalonia does not consider the implementation of horticultural systems on the rooftops of buildings. A respondent who attempted to install a RTG on the top of his restaurant (to produce his own local and fresh vegetables) was declined permission due to strong legal barriers, which he did not manage to overcome even after meeting with several departments of the Barcelona City Council and adapting the project to their requirements:

> *Although the project was already designed, it couldn't be implemented. During 2 years (2010–2011) the project was negotiated with different departments of the city council, but the final answer was always negative. At the end, the innovation aspect of the project was not valued […] Barriers were, first, planning, because we are located on the waterfront and zoning documentation does not consider food production as a potential use; then, the barriers changed to the urban landscape because all restaurants situated on the waterfront were all designed the same way and the local administration was unsure about changing this pattern. Finally, the barriers were related to ownership. I rent this space, and the contract expires in six years, and the city council did not guarantee the contract extension to ensure the payback of the infrastructure (RTG promoter).*

### (iii) Social aspects

Different stakeholders point to a variety of social opportunities emerging from URFs, although opportunities depend on the type of UA to be implemented in URFs. As a result, the social values attached to commercial URFs are only related to the local production of food, while stakeholders identify further social benefits for community activities, such as community building. Several stakeholders underline the current social values created by UA initiatives in Barcelona as well as the growing interest in the creation of cooperatives. These coops boost local food consumption and revitalize the local community, enhance learning, and create a meeting place in the neighbourhood for socializing.

Furthermore, the increase in consumer awareness was one of the aspects of UA that interviewed stakeholders valued most. Becoming involved in UA activities enhances the valuation of seasonal, organic, and environmentally friendly food products as well as the growth of value-added products (e.g., marmalade). Several respondents highlighted that URF would allow children to learn about the origins of the foods they consume and adults to become more conscious of seasonal and quality products by participating in learning activities in buildings just around them in the city. The increase in consumer awareness and knowledge is one of the social aspects of UA that professional farmers from periurban areas value the most:

> *URF can be a way for increasing the awareness and knowledge about periurban and professional agriculture. However, this "real" agriculture should also be explained when promoting UA activities (BLLAP managers).*

However, stakeholders also identified different social barriers to the development of URF. Low user acceptance could lead to a lack of involvement of neighbours in community URFs, particularly when there is no real need for producing one's own food. Several stakeholders even highlighted the potential social indifference of customers likely to keep seeking their perfect red tomatoes rather than becoming aware of the value of local products. Moreover, the occupation of the rooftops and the potential use of URFs in residential buildings could have several management barriers. For food production initiatives, the lack of trained personnel could become a constraint. Finally, when implementing RTGs, a lack of social acceptance of soil-less techniques may arise. In some cases, social disparities and a lack of financial resources can also become important constraints because RTGs require a high capital investment compared to RF or soil-based UA forms.

### (iv) Economic aspects

The local production of food using URF can considerably reduce costs related to food production and consumption, mainly because of the avoided distribution step, which also represents a decrease in food losses during the lifecycle of horticultural products. Moreover, the efficiency related to RTG would also mean a reduction in production costs due to a reduction in crop inputs consumption (e.g., water). Finally, an RTG that exchanges flows (i.e., water or energy) with the building would boost resource efficiency. Rooftops are currently unproductive spaces in cities (90% of roofs in Barcelona) and most of the stakeholders noted the importance of valuing these spaces as a resource. Stakeholders emphasize that growing crops on rooftops, similarly to producing solar energy on rooftops, is compatible with other land or roof uses in a city, particularly in dense cities such as Barcelona, where space is limited.

However, several respondents (e.g., NGOs, food coops, local administration, urban gardeners) perceive URF as an expensive system (particularly RTG) with economic barriers expected due to the narrow margin from sales of horticultural products. To allow urban producers engaged in URF to earn a decent salary, the price of urban produce may need to be high, thus creating affordability issues for local residents. Notwithstanding these barriers, some stakeholders noted that URF may have some added value because it may become a brand (e.g., “tomato from Barcelona”). Furthermore, URF can enhance the positive image of a company or contribute to its Corporate Social Responsibility (CSR) goals (e.g., educational programs). Different locations can be used to implement RTGs with this objective, ranging from hotels to shopping malls and restaurants. As an urban planning lawyer explained:

> *The topic is interesting also for the own image [of companies], such as a restaurant or a store that could sell the product that is cultivated on its rooftop (garden). This gives an added value to both the product and the company. When observing the greenhouse attached on the building of a restaurant or a shop, the consumer can directly identify them as companies that promote local vegetables [for their consumption or their retail] (Urban planning lawyer).*

Finally, both UA and URF were identified as good opportunities for improving local economic trends and creating innovative and green jobs as part of the green economy and the environmental sectors. In a country such as Spain where unemployment is rampant, URF can unleash entrepreneurialism and promote new economic projects:

> *It can be an opportunity for addressing the current financial crisis. Unemployment rates are high and entrepreneurship is an option. Moreover, people have the time for self-organizing to access an unused space which, with a certain inversion, can return a profit (Generalitat de Catalunya).*

## 3.4. Discussion

This study has examined the promotion and inclusion of new types of urban agriculture through the practice of urban rooftop farming. It contributes to the nascent literature on the stakeholder and public perceptions of urban agriculture and exposes how those perceptions shape the development of new urban agriculture practices and projects.

### *3.4.1. Contrasts in the definition and values attributed to UA in Barcelona*

The FAO defines urban agriculture as growing plants and raising animals within cities. However, the scholarly literature offers multiple definitions about UA, from definitions where UA is limited to horticultural activities, animal husbandry is excluded from UA, or the periurban fringe is included in UA (such as in Taylor and Taylor Lovell 2012; Giacchè and Tóth 2013; Mok et al. 2013; Tornaghi 2014). This also occurs when defining UA in Barcelona where the stakeholders we interviewed had diverging opinions of what constitutes UA, based on the values they attach to it (i.e., social or food production), the professionalization degree of gardeners (i.e., real or amateur agriculture) and the spatial situation of the plot (i.e., periurban or urban agriculture). These different views create an ambiguous starting point for further developing UA initiatives because the way UA is perceived strongly depends on the conceptualization of UA itself. There is thus a need to formulate a common definition of UA in Barcelona to alter the fact that different groups of stakeholders base their perceptions on contradictory definitions. A common definition would help establish the grounds for a growing UA in Barcelona in which a diversity of stakeholders can take part.

In developed countries, food production is generally seen as the common driver for UA activities, even in projects that address strong social needs, such as community building (Kortright and Wakefield 2010; Carney 2011; Kirwan and Maye 2012; Taylor and Taylor Lovell 2012; Smith et al. 2013; Mok et al. 2013). For example, the Growing Power project in Milwaukee, which works to enhance community access to fresh and healthy food, education opportunities, and food justice, produces a significant amount of food. Nonetheless, stakeholders in Barcelona clearly differentiate between social UA and productive UA, instead of identifying a social and productive UA. As a result, food production is not the main goal of current UA projects. This is related to three main aspects: the origin of UA, the specific urban morphology of Barcelona, and the lack of food planning priorities in the city. First, in Barcelona UA activities originated from social and therapeutic motivations, whereas in other regions of the world UA often arose as a response to episodes of food insecurity (food shortages, wars) (Kortright and Wakefield 2010). In such cases, UA is still largely a food production activity with some additional social benefits on the side. Second, stakeholders in Barcelona do not link UA to a significant potential for food production due to the small size of land resources available in the city. Finally, although food planning is a hotspot in urban agriculture development (Morgan 2009; Morgan and Sonnino 2010), it is still absent in the Catalonian food and agriculture legislation and in the UA development framework in Barcelona.

As a result, UA in Barcelona is largely developed and promoted for its social value rather than for food production, which shapes the place given to URF in the development of UA in the city. Thus, instead of solving food problems by promoting productive UA activities, public-supported UA models can be linked to green washing practices (Tornaghi 2014). While URF aims to increase food yields and urban productivity (Despommier 2010; Germer et al. 2011; Despommier 2011; Cerón-Palma et al. 2012), most stakeholders did not view such techniques and practices positively. Therefore, the acceptance of URF and its potentialities mostly relies on shifting the driver of UA from social values to food production itself. Moreover, as perceptions of "local products" and local food production mostly concern periurban areas (whereas the city itself is not perceived as productive), institutional efforts to promote local production and consumption are concentrated on periurban farming, such as the Baix Llobregat Agricultural Park (BLAP) (Paül and Tonts 2005; Paül and McKenzie 2013), rather than on the farming of urban areas themselves.

Despite the fact that UA and URF respond to the challenges of regional and local environmental policies, such as climate change mitigation and adaptation, such discussions are currently missing in the urban sustainability policies of Barcelona. This absence is contrary to global trends that progressively include UA in local sustainability policy (McClintock 2010; Mok et al. 2013), such as London's zoning policy (London Assembly 2010) and Chicago's GO TO 2040 policy (Chicago Metropolitan Agency for Planning 2010). Thus, the absence of UA in the current sustainability policies of Barcelona suggests that the perception of UA as a socially oriented activity rather than as a food production activity only slows down the process of creating UA policies and institutionalizing them through sustainability planning. There is a lack of trust in the sustainability benefits of local production. Consequently, the municipality privileges other strategies (e.g., sustainable mobility).

Our results show that defining more equitable UA forms that can help achieve greater food sovereignty, and can offer an alternative to the current food system are greatly relevant. This trend is common in UA movements (Block et al. 2011) because UA is seen as a potential mechanism for political and social change (Cohen et al. 2012). The importance of avoiding existing social disparities present in alternative local food movements (Guthman 2008), such as reduced access to RTG products (Ackerman 2011), is a key issue for some stakeholders, mostly those who are currently involved in UA activities.

### *3.4.2. Environmental, social, and economic barriers and opportunities for URF*

In this study, we identified several barriers and opportunities, and compared them to two previous studies on the topic of URF (Table 2). In 2012, Cerón-Palma et al. (2012) analyzed the barriers and opportunities of RTGs through expert roundtables. In 2013, Specht et al. (2013) reviewed the benefits and limitations of urban ZFarming (understood as building-related urban agriculture forms).

Our study not only identified common environmental opportunities for URF, such as carbon fixation (as demonstrated by Jun Yang et al. (2008) for green roofs) but also pointed to new opportunities for RF (recycling of organic waste) and for both RF and RTG: increasing horticultural yields, enhancing closed cycles, and improving the habitability of buildings. However, environmental barriers differed from previous studies and no environmental barriers were found for RF. Finally, the integration of URF into existing buildings was noted as a technical barrier, although several other barriers were added: logistical constraints, crop management limitations, and legal barriers for rooftop usage.

In terms of social opportunities, respondents highlighted the enhancement of food security (Kirwan and Maye 2012; Barthel and Isendahl 2013), the linkage of consumers to food production and the provision of educational tools on food production (Kortright and Wakefield 2010). Beyond previous studies, stakeholders also valued community building and an increase in consumer awareness as social opportunities for URF. In addition, we identified a lack of training, user acceptance and involvement, and management (i.e., in community models) as barriers.

The valuation of unproductive spaces (defined as "wasted spaces" in Gorgolewski et al. [2011]), a reduction in costs, local development, and potential transformed products stemming from URF were the key economic opportunities that stakeholders mentioned. However, our study also revealed the importance of Corporate Social Responsibility and the positive image that companies can harness when implementing sustainable systems, such as URF. Regarding economic barriers, the narrow margin of URF products (such as in the Catalan market), competition with other uses and investment costs (particularly for RTG) were similar to the ones mentioned in previous studies. Consumer acceptance was an economic barrier underlined in our study because some stakeholders perceived air pollution or soil-less techniques as potential constraints. In contrast to Specht et al. (2013), stakeholders did not note that URF commonly focus on the production of certain crops (e.g., vegetables) while excludes other types of food, such as rice or wheat.

## 3.5. Conclusions and future actions

Following global trends, UA is spreading throughout Barcelona, mainly as a response to the current financial crisis that has created vacant plots of land around the city (due to the collapse of the construction sector) and an increase in demand for urban gardens. There are multiple perceptions of UA and URF in Barcelona, which reflect the plural definitions that stakeholders assign to urban agriculture. Our results show the presence of three differentiated groups. Periurban actors conceptualize urban agriculture as a false agriculture and, as a result, they do not support UA or URF. Some stakeholders (i.e., local administration, urban gardeners, NGOs, food coops) conceptualize UA only as a socially oriented activity and exclusively support soil-based UA. Last, other stakeholders groups (i.e., regional and local administration, architects, urban gardeners) do support both UA and, in particular, URF, and highlight the potential food production of these systems.

Contrary to other cities where UA has recently grown, a social-production conflict exists when supporting URF activities in Barcelona due to the origin of UA, the urban morphology, and the lack of a food planning framework. Consequently, the main driver of UA projects in Barcelona is addressing social needs rather than food production needs. However, stakeholders who support URF systems also claim that these projects can support urban food production, thereby changing the driver of the current socially oriented UA to a productive UA.

In this sense, Urban Rooftop Farming (URF) is perceived as an innovative way of producing food within city limits by using unused space on buildings. However, some stakeholders negatively perceive soil-less techniques and the use of greenhouses (Rooftop Greenhouses, RTGs) because they do not consider potential improvement in crop efficiency as an important variable in a cost-benefit evaluation. URF supporters particularly value RTGs because greenhouses and buildings can exchange residual flows (e.g., residual heat, residual $CO_2$) and simultaneously optimize food production and building systems. Despite the potential of URF, some barriers include economic investment, potential disinterest of users and consumers, and current legislation that already blocked an RTG project in the city of Barcelona.

Even so, various actions can help lift such barriers, particularly through the participation of the administration, research institutes, and private initiatives into the concrete planning of RTG projects. Research entities already involved in the study of URF would need to cover research gaps and determine the sustainability balance of URF (covering both potential benefits and impacts). Finally, private companies could promote URF in Barcelona by financing pilot projects or developing their own entrepreneurial rooftop farming initiatives (similarly to companies in North America). Current legislation and bureaucracy, such as zoning, should also be revisited to ease the implementation of URF. For instance, the incorporation of food production as a potential use of rooftops in the planning legislation may weaken existing legal barriers to URF. A greater endorsement of new projects by different municipal departments would also bestow a greater legitimacy to URF. These departments may play key roles in the revision of the legislation, in the development of local policies to promote local production, and in the dissemination of information on the benefits of URF.

Finally, the results of this study demonstrate that pilot projects are necessary for verifying the feasibility of URF systems, obtaining results (e.g., the potential energy savings of RTGs in a service building), and communicating the potentialities of URF to legislators and planners. Moreover, the use of pilot projects for education would help avoid the negative preconceived opinions expressed by potential urban gardeners and consumers. Thus, most of the stakeholders highlighted the need to create a new school that allows citizens to learn about agriculture by participating in workshops and initiating people into agricultural work. As stated by an urban gardener, pilot projects may allow people to “See, understand, live, and know the system.”

# Chapter 4

## Integrating horticulture into cities

### A guide for assessing the implementation potential of Rooftop Greenhouses (RTGs) in industrial and logistics parks

Picture: *Tomato production in the RTG-Lab (Bellaterra, Spain)*
*(©Esther Sanyé-Mengual)*

# Chapter 4

This chapter is based on the journal paper:

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## Abstract

Recently, the application of Rooftop greenhouses (RTGs) to integrate agriculture into cities has increased, although the area where they can be potentially implemented has not been quantified yet. Consequently, this paper aims to design a guide to evaluate the potential implementation of RTGs in industrial and logistics parks and to apply the guide to the case study of Zona Franca park (Barcelona, Spain). 8% of the rooftops were identified as feasible for a short-term implementation of RTG, according to the defined technical, economic, legal and agricultural criteria. Estimations indicated that the annual tomato production in this area could account for almost 2,000 tones, which is equivalent to the yearly tomato demand of 150,000 people. Besides, this production could substitute imported tomatoes and avoiding their distribution would represent savings of 65.25 t of CO2 eq·m$^{-2}$.

Keywords: cities, urban agriculture, food self-sufficiency, rooftop greenhouse, industrial and logistics parks.

## 4.1. Introduction

Research on the potential self-sufficiency of urban resources has mainly focused on sustainable strategies applied to energy, water, urban planning, waste management and materials, while the food flow and local production have not been deeply analyzed yet. However, urban farming and urban self-sufficiency are an emerging issue in the design and transformation of cities (Inayatullah 2011). This fact results from four urban issues: the urban dependency on external resources (Girardet 2010), the importance of urban food production for achieving self-reliance in a globalized world (Grewal and Grewal 2012), the need of facing the food production issue in sustainable urban design (Meijer et al. 2011) and the increase in the number of both spontaneous and planned experiences in urban agriculture (Torreggiani et al. 2012; Mok et al. 2013).

Displaced by urban growth, agricultural production areas moved away from urban areas and, consequently, from the main centres of consumption. The driving forces of this separation were, first, the urban sprawl of residential areas throughout flat and often fertile areas and, second, the increasing urban specialization in the tertiary sector (Duranton and Puga 2005). Besides, when the industrial and logistics sectors were relocated to the periurban areas by the creation of industrial and logistics parks, the periurban agriculture was also displaced further away.

The design of industrial and logistics parks is characterized by large industrial plants and warehouses, where companies from different sectors are located. The activities performed in these parks commonly require large amounts of energy and water. For example, energy consumption is mainly related to industry and freight transport, sectors that accounted for 68% of the energy consumption in Catalonia (ICAEN 2009). Apart from being located near cities, these parks are usually well connected to the main transportation clusters, such as ports, airports and freight rail stations. Normally, the developers of these facilities are public agents, who invest in the infrastructure and become the managers and owners. Besides, logistics parks near main cities typically concentrate large food distribution centres, which take advantage of the proximity to cities (e.g., in Spain, most major cities have a food distribution centre in the nearest park).

The little use given to the rooftops in industrial and logistics parks has focused on solar energy systems, which increase the urban renewable energy generation. In Spain, photovoltaic electricity production has grown from 5.900 to 8.300 GWh between 2009 and 2013 (EurObserv'ER 2014). According to ASIF (2011), approximately 54% of the new photovoltaic installations in Spain during 2010 were placed on the roofs of industrial buildings. However, other constrained resources can now be stored or produced in cities through new technologies and techniques implemented on roofs. For example, rainwater harvesting (RWH) can represent a way to prevent water scarcity, and studies have already demonstrated that RWH systems are not only environmentally (Angrill et al. 2012) but also economically feasible (Farreny et al. 2011a). Furthermore, green strategies (i.e., green roofs, green walls and green facades) have been also applied on urban buildings to improve their energy efficiency (Cerón-Palma et al. 2012; Saadatian et al. 2013). Alternatively, different technologies, commonly known as vertical farming (Despommier 2011), enable the growth of agricultural products on urban buildings.

Within urban areas, the awareness of local food has led to an increase in urban agriculture experiences (Taylor and Taylor Lovell 2012; Mok et al. 2013). Even more, urban agriculture has currently become an extensive land use in some cities, such as Chicago (Taylor and Taylor Lovell 2012), as well as an alternative use for vacant lands (McClintock et al. 2013). Urban agriculture spreads across cities in multiple forms: community farms, community gardens, commercial farms, institutional farms, rooftop farms or private gardens (Cohen et al. 2012). Moreover, the administration is working towards the integration of agriculture into the city zoning and planning, such as the *GO TO 2040* regional plan of Chicago (with an entire section for sustainable local food systems) or the works of the Planning and Housing Committee regarding urban food growing systems and planning (London Assembly 2010).

As a result, food production has become an important issue in the field of planning and architecture. For instance, the American Planning Association has developed a guide for local food production planning (Hodgson et al. 2011) and the American Society of Landscape Architects has identified urban agriculture as a sustainable element in urban planning (ASLA 2011). At educational level, buildings that incorporate food production have become the focus of design and architecture students, such as in the “Carrot City, Designing for urban agriculture” works (Lee-Smith 2009). Furthermore, the development of sustainable design and planning (e.g., LEED program for buildings) emphasizes the introduction of innovative systems into buildings, such as building-integrated agriculture (Komisar et al. 2009). In this sense, the development of tools for identifying the potential of urban agriculture systems can help planners and managers in the design of future sustainable cities.

### *4.1.1. Urban agriculture on buildings: Rooftop greenhouses*

Rooftop Greenhouses (RTGs) consist of implementing a greenhouse on the top of a building. The system aims to produce food within the urban frame through soil-less culture systems (i.e., hydroponic, substrate, aeroponics) in order to reduce the structural load on the building while increasing the resource efficiency.

Current RTG projects are mainly horticultural commercial activities and are concentrated in urban areas of North America. Gotham greens (Brooklyn, NY) (http://www.gothamgreen.com) has a 1.400m$^2$-RTG for greens production (6 varieties of lettuce and basil) and it is planning to install 2 new RTGs to increase its overall production area up to 18.000 m$^2$. Also in New York, the store The Vinegar Factory (Manhattan) produces its own fruits and vegetables in a 830 m$^2$-RTG (http://www.elizabar.com). Lufa Farms (Montreal, Canada) (https://lufa.com/) built up an RTG of 2,900 m$^2$ on a commercial building to cultivate not only greens (lettuce and herbs) but also other horticultural products (e.g., tomatoes, eggplants) in different thermal zones. Other RTGs are also planned in these areas for housing projects, such as the Forest houses project (a residential building with a 930m$^2$ RTG in South Bronx, NY), or educational purposes (e.g., the Cypress Hills Community School or the Manhattan School for Children). In Europe, the implementation of RTGs is still incipient and there is only information about some projects, such as the INFarming (Fraunhofer UMSICHT 2011) and the “Fresh from the roof” experiences, both in Germany.

Most of the presented RTGs use hydroponic and substrate culture systems. Controlled environment technologies are commonly used when cultivating different vegetables in the same RTG (i.e., Lufa Farms). Regarding commercialization options, some companies have their own market place (i.e., The Vinegar Factory) or sell their produce in supermarkets under a local production label (i.e., Gotham greens) while others work with a Community Supported Agriculture (CSA) model (i.e., Lufa farms) (Resh 2012).

In the Mediterranean area, several environmental, social and economic benefits of RTGs have been identified (Cerón-Palma et al. 2012). Focusing on the environmental benefits, RTGs will offer benefits not only to the building and the city but also to the food system (Despommier 2011; Cerón-Palma et al. 2012). First, RTG systems improve the insulation of roofs, reducing the energy requirements for heating and cooling (up to ≈40% for specific case studies) (Cerón-Palma et al. 2011; Cerón-Palma et al. 2012). Furthermore, although current RTGs are isolated from the building, future RTGs are expected to integrate their flows (i.e., heat, waste, water and $CO_2$) into the metabolism of the building to optimize the resource use (Cerón-Palma 2012).

Second, RTGs are expected to be implemented in already built surfaces, most of which are currently unproductive spaces, making cities more multifunctional by integrating food production into buildings. Other environmental benefits are related to promoting local food production, which reduces the transportation requirements and the consequent environmental impacts (Despommier 2011; Cerón-Palma et al. 2012; Sanyé-Mengual et al. 2013). In terms of agronomic issues, RTG horticulture considers the same principles as in commercial agriculture, which corresponds to the principles of Good Agricultural Practices as recently defined by FAO (2013b). Among other issues, these principles consider the integrated pest management and plant hygiene procedures, which include the use of living organisms for biological control to reduce the use of pesticides. Finally, the use of rooftops for food production avoids the most common food risk in urban agriculture: soil contamination and the consequent bioaccumulation of metals (Clark et al. 2008; Kessler 2013; Swartjes et al. 2013; Bugdalski et al. 2013; Mok et al. 2013; Mitchell et al. 2014). Regarding air pollution, although it affects vegetation by accumulating trace metals, it depends on the location of the agriculture activity and, specifically, on the distance to traffic hotspots (Bell et al. 2011; Säumel et al. 2012). Besides, this can be managed more easily in protected crops (i.e., RTG) than in open fields (e.g., urban gardens).

Current research on vertical farming and RTGs focuses on their implementation on buildings within the urban frame (e.g., residential) (e.g., Cerón-Palma et al. 2011; Fraunhofer UMSICHT 2011; Scott 2011; Despommier 2011; Cerón-Palma et al. 2012). Nevertheless, the identified economic and social barriers for RTG systems in the Mediterranean area (Cerón-Palma et al. 2012) suggests that industrial and logistics parks could be more suitable areas for implementing commercial RTGs. First, these systems can be implemented more easily and effectively on solely owned roofs than on buildings with multiple owners (e.g., residential buildings) by overcoming potential management barriers. Second, current RTG projects have been developed on large roofs, such as Gotham Greens (1,400 $m^2$-RTG) or Lufa Farms (2,900 $m^2$-RTG). Hence, the implementation of RTGs on larger roofs may reduce economic barriers (e.g., decrease in the payback time) and increase production volumes. Furthermore, the rooftops of industrial and logistics parks are usually more homogeneous in terms of shape and materials than residential ones, making easier the implementation. Third, as large energy consumers, the implementation of RTGs in industrial and logistics parks can result in a significant reduction of heating and cooling requirements due to thermal insulation and flow synergies created by RTGs.

### *4.1.2. Goal and scope*

Notwithstanding the identified potential benefits of RTGs in urban areas, there is a lack of procedures, criteria and tools to assess the implementation of RTGs on buildings. Thus, stakeholders (e.g., planners and business managers) cannot evaluate the potential implementation of RTG projects and their benefits in a study area.

The purpose of this paper is to design a technical step-by-step guide to identify the implementation potential of RTGs in industrial and logistics parks in urban areas. The expected users of this tool are planners and professionals that aim to assess the implementation of RTGs at a large scale. RTGs can be implemented in projects as a sustainable strategy to develop new logistics and industrial parks or to rehabilitate the existing ones. Furthermore, the last step of this tool aims to provide quantitative indicators for a valuation of RTG projects from the environmental and self-sufficiency perspectives. Therefore, in the decision-making process stakeholders can take into account not only the potential itself (i.e., feasibility and potential implementation area) but also the environmental and self-sufficiency performance of RTGs. Secondary objectives are applying the guide to a case study in Barcelona (Catalonia, Spain) and quantifying the potential environmental benefits and self-sufficiency potential.

## 4.2. Methods: A guide for assessing RTG implementation

### *4.2.1. Guide overview and scope*

The guide follows three steps. First, the criteria to identify feasible rooftops for the implementation of RTGs are defined based on expert consultations. This is the most important step and determines the feasibility of implementing RTGs, by considering from basic (e.g., legal framework, economic feasibility) to specific factors (e.g., agricultural limitations). Second, the RTG implementation area of the entire park has to be accounted for by means of geographic information systems (GIS). This step allows to compile the data of large areas and to apply the criteria defined in Step 1 in order to determine the total area of feasible rooftops. Finally, the guide includes the quantification of environmental and self-sufficiency indicators so as to provide stakeholders with complementary information for evaluating the implementation of RTGs. The environmental benefits are assessed from a life cycle perspective (Figure 4.1).

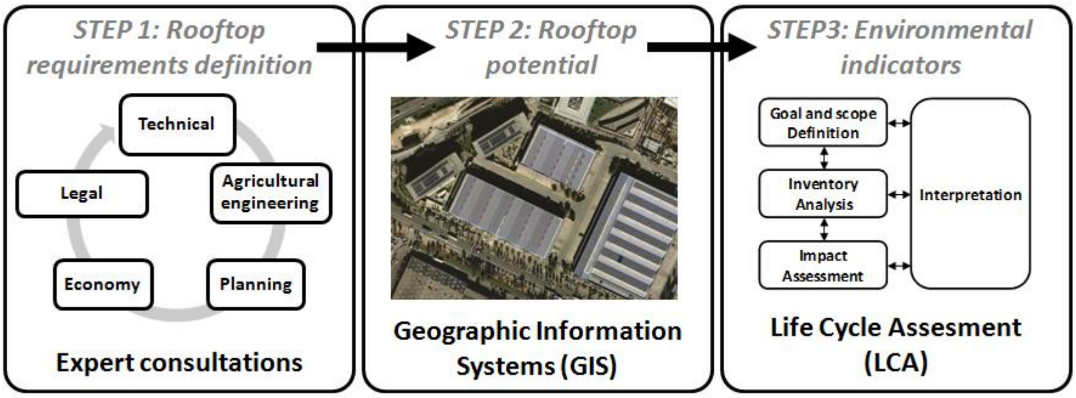


***Figure 4.1.*** *Guide diagram: steps and tools followed during the study.*

Different business models and potential uses have been observed in current RTG projects (e.g., from research centres to commercial experiences). Nevertheless, the present guide focuses only on one type: commercial RTGs. Therefore, the guide requires the economic feasibility of the agricultural activity. As observed in current experiences, the guide assumes that the RTG system consists of a soil-less culture system to reduce structural loads on the building. Finally, this guide addresses the implementation of RTGs in compact urban areas.

### Step 1: Definition of the requirements for implementing RTG

Five issues are basic to determine the feasibility of implementing RTGs: planning, agriculture, economy, legal requirements and technical aspects (Figure 4.2). The criteria for each issue are defined through consultation with experts, which also considers the barriers and limitations to the implementation of RTGs already mentioned in the literature (Cerón-Palma et al. 2012; Specht et al. 2014).

The ideal composition of the panel might include experts from the abovementioned issues: planners, agronomists, economists, public administration, engineers and environmentalists. Furthermore, the panel can be complemented by incorporating members from urban agriculture experiences (e.g., urban gardeners), companies from the study area (e.g., company placed on the industrial park) or local producers. For the definition of the present guide, the panel of experts was composed by architects, agronomists, structural engineers, experts from public bodies and an urban planning lawyer. The experts were from both private companies and research institutes. Furthermore, some of the experts were already involved in RTG projects (e.g., design, legal assessment) and others had expertise on the design of industrial parks or on the implementation of sustainable technologies on rooftops (e.g., solar energy). Each expert contributed to a different criterion in accordance with their knowledge (Table 4.1). For the criteria definition, the experts also considered the following requirements: data availability for validating the criteria, logic and understandable criteria for stakeholders, and representation of barriers that real experiences have faced in the study area.

***Table 4.1.*** *Description of the panel of experts: Expert, area of expertise, relation to RTG and involvement in criteria definition [criteria areas: planning (P), agriculture (A), economic (E), legal (L) and technical (T)].*

| **Expert** | **Area of expertise** | **Expertise on RTGs** | **Criteria definition** | | | | |
|---|---|---|---|---|---|---|---|
| | | | **P** | **A** | **E** | **L** | **T** |
| Architects (3) | Design of green architecture<br>Integration of sustainable strategies in design<br>Development of green strategies (e.g., green roof) | Design of RTG projects<br>for new buildings<br>Design of RTG projects<br>for rehabilitation of buildings | X | X | | X | X |
| Agronomists (2) | Design of Mediterranean greenhouses<br>Environmental assessment of greenhouse production<br>Assessment of soil-less systems<br>Studies on eco-efficiency of greenhouse technologies | Design of greenhouses<br>for RTG purposes | | X | X | | X |
| Structural engineers (2) | Design and assessment of industrial and logistics parks<br>Expertise on construction materials | Knowledge regarding industrial and logistics<br>parks structure | | | | X | X |
| Urban planning lawyer (1) | Assessment of urban planning projects towards urban agriculture and sustainability<br>Involvement in rooftop usage projects | Assessment of RTG projects | X | | | X | |
| Administration (6) | Development of urban agriculture projects<br>Participation in projects of solar energy implementation<br>Definition of the legal framework for solar energy implementation in rooftops | Knowledge of the rooftop usage legal framework | X | | | X | |

*Planning criteria*

Building features and rooftop usages are defined in planning ordinances, and thus the installation of a greenhouse on the rooftop must be allowed by the current zoning framework. However, greenhouses are not commonly included in zoning documents due to the lack of RTG experiences. As a result, real RTG projects in Catalonia had to modify the current planning to include this new rooftop usage. Hence, planning specifications and their (lack of) flexibility can result in a restricting criterion and it must be checked when assessing the feasibility of RTGs.

Planning documentation and administrative processes might be checked to determine whether planning barriers can be overcome or not. The verification process might be done from the national (i.e., global planning) to the local level (i.e., different urban pieces have their own planning). The variables to check are (a) limitations on the implementation of rooftop equipments, (b) limitations on the implementation of a greenhouse structure (e.g., height restrictions) and (c) the possibility of modifying planning specifications. Planning documentation can be requested to public entities or real RTG projects can be consulted to observe potential planning barriers. This criterion is geographically sensitive as planning conditions may vary between regions and countries.

*Agriculture criteria*

Agriculture criteria are based on the requirements of the activity implemented on the rooftop. They are related to the dimension of the RTG structure and to the factors which limit agricultural production. On the one hand, rooftop availability must be verified to implement RTGs. In contrast to other rooftop usages that can be adapted to the space availability (e.g., solar panels), greenhouses may occupy almost the entire area of the roof. On the other hand, since the guide is devoted to commercial RTGs, crop yields must be ensured in the agriculture production. However, within an urban environment with buildings of different size, sunlight can become a constraint criterion because shadowed areas will have lower yields (Castilla 2012). Therefore, both occupied and shadowed areas will be excluded from the potential implementation area of RTGs. The validation process of these criteria should be (a) identifying whether the area is completely available and sunny, and (b) if not, differentiating those available or sunny spaces of the rooftop from the non-feasible areas. Both criteria can be validated through GIS data (i.e., orthophotomap or aerial images of the study area) or fieldwork. Although shadows can affect the greenhouse for a short period of the day or for the whole day, GIS layers only show the study area for a specific time in the day. Nevertheless, shadowed areas in the GIS are identified as non-feasible since the crop yield is drastically affected by shadows, independently from their duration. Data might be compiled in the rooftop database (see Step 2).

*Economic criteria*

As a commercial activity, the economic feasibility of RTGs must ensure that costs related to the initial investment and the production costs can be met by the production income (i.e., payback is feasible). Therefore, the size of the RTG should be large enough to satisfy the economy of scale of the activity. The areas of commercial RTGs in North America and Central Europe range between 400 and 9,300 $m^2$. Hence, a minimum area should be defined to determine whether the implementation of an RTG is economically feasible. This criterion will be verified through GIS tools and the area of each roof. The economic criterion is geographically sensitive.

*Legal criteria*

Commonly, Mediterranean greenhouses are light structures made of steel and a plastic cover, with an average weight of 8-12 $kg \cdot m^{-2}$ (Montero et al., 2011). However, according to real RTG projects, the implementation of greenhouses in buildings must accomplish current housing laws (e.g., Technical Building Code (Spanish Government, 2006)) rather than usual greenhouse standards (i.e., EN 13031 (CEN 2001)), as well as security and fire prevention regulations. In this sense, the greenhouse design is expected to accomplish this legal framework (e.g., by reinforcing the structure). The verification process might check (a) whether the greenhouse design accomplishes the legal building requirements and (b) if not, whether the structure can be adapted. Legal documents on buildings should be consulted to check the legal requirements in urban areas (e.g., technical code, building laws, security laws). This criterion is geographically sensitive, as building laws and requirements may vary between regions and countries.

*Technical criteria*

The technical characteristics of a roof can be a barrier for implementing RTGs due to its slope and resistance. First, the slope might range between 0.5 and 2% to develop the agronomic activity, as defined in common practices among greenhouse developers. It allows draining rainwater and avoids an excessive thermal stratification of the greenhouse air. In this sense, flat roofs are technically feasible for implementing RTGs. Second, the material and structure of the rooftop must be resistant to match the load requirements of the greenhouse. Pursuant to opinion of the panel of experts, reinforced concrete yields more stability for rooftop usage and ensures structural strength for implementing RTGs. In contrast, roofs made of metal (which can be both steel and aluminium structures) would have to be reinforced in a rehabilitation process. Both criteria (i.e., type of roof and material) determine the technical feasibility. Furthermore, mid- and long-term feasibility includes the use of technical solutions for implementing RTGs (i.e., reinforcement or adaptation) (Table 2). The scenarios might be evaluated using GIS and collecting fieldwork data (i.e., type of roof and material).

***Table 4.2.*** *Definition of technical feasibility scenarios, according to the type of roof and its material.*

| | | **Type of roof** | |
|---|---|---|---|
| | | **Flat** | **Sloped** |
| **Roof material** | **Reinforced concrete**<br>(Resistant) | **Short-term feasibility**<br>Direct implementation | **Long-term feasibility**<br>Rehabilitation/ Adaptation<br>New construction |
| | **Metal roofs**<br>(Not resistant) | **Mid-term feasibility**<br>Roof reinforcement | |

*Geographical variation*

The criteria were designed in the context of a specific case study. However, they can be applied to other case studies and geographical areas. This may lead to variations in three criteria depending on the geographical context:

- The planning criterion relies on the flexibility of the legal framework. Hence, it will vary between countries with and without planning rules.
- The economic criterion defines a minimum area to implement a commercial RTG. This area depends on the agriculture sector context (e.g., heated or unheated technologies, average greenhouse extension of the study area, productivity rates and payback times). Mediterranean unheated greenhouses (e.g., multitunnel greenhouse) need a lower investment and the production requires less energy than heated greenhouses in central Europe (e.g., Venlo greenhouse). As a result, the minimum area in a Mediterranean context will be smaller than in central Europe.

- Technical criteria are based on the current legal framework of the building sector. For instance, regarding technical properties, a legal framework dealing with rooftop usages (i.e., solar systems) will ensure an easier implementation of RTGs, as rooftops will be already prepared for an increase in the structural load.

### Step 2: Potential implementation area quantification

Once the criteria were defined by the panel of experts, different types of data should be compiled to evaluate their requirements. Rooftop data can be retrieved from several sources: land registry files (i.e., area, year of construction), construction projects (i.e., technical properties), public planning projects (i.e., area, use of the building) and cartography, in the best cases. However, compiled rooftop data are not currently available to evaluate the different criteria.

GIS (GVsig 1.11 software) was used to manage the information by creating a multi-data spatial layer: the rooftop database. It compiled the data necessary to evaluate the implementation criteria for each rooftop (Table 4.3). First, the cartography needs to be obtained from a database or generated based on an orthophotomap or aerial images. Next, roof data needs to be compiled or obtained from field-work (e.g., material). Third, the characteristics of the building (e.g., use) are obtained from bibliographic data (i.e., cadastre). Finally, the technical and economic feasibility are specified through GIS according to the defined criteria (Step 1).

***Table 4.3.*** *Variables of the rooftop database, sources, specific indications and relation to the criteria.*

| Variable | Source | Specific indication | Criteria |
|---|---|---|---|
| *Rooftop availability* for RTG implementation | Field-work | The unavailable area on large rooftops should be distinguished | Agriculture |
| *Rooftop shadow* | Field-work | The non-shady areas of large rooftops should be distinguished | Agriculture |
| *Roof type* | Field-work | Roofs can be Flat, Inclined, Gabled, Hipped or Amorphous | Technical |
| *Roof material* | Field-work | Primary materials are concrete and metal | Technical |
| *Year of construction* | Cadastre/Project | Data for roof characterization | - |
| *Use of the building* | Cadastre/Project | Data for roof characterization | - |
| *Roof area* | Calculated in the GIS layer | | Economic |
| *Technically feasible rooftops* | Identified in the GIS layer | Identification of flat and concrete roofs | Technical |
| *Economically feasible rooftops* | Identified in the GIS layer | Specified according to the minimum roof area required | Economic |

The potential implementation area was quantified through GIS by considering the criteria defined in Step 1. As a result, the combination of certain characteristics determines whether a rooftop is feasible. Table 4 compiles the characteristics that a rooftop must accomplish to be identified as feasible in the short- and mid-term. After determining the technical and economic feasibility of each rooftop in the GIS layer, the total area of economically feasible rooftops account for the RTG potential of the entire system (i.e., industrial park).

***Table 4.4.*** *Identification of technical and economic feasibility in the GIS process, according to combination of variables*

| **Variable** | **Short-term feasibility** | | **Mid-term feasibility** | |
|---|---|---|---|---|
| | **Technical** | **Economic** | **Technical** | **Economic** |
| *Rooftop availability* for RTG implementation | Available | Available | Available | Available |
| *Rooftop shadow* | Non-shadowed | Non-shadowed | Non-shadowed | Non-shadowed |
| *Roof type* | Flat | Flat | Flat | Flat |
| *Roof material* | Concrete | Concrete | Metal | Metal |
| *Roof area* | - | >500 $m^2$ | - | >500 $m^2$ |

## Step 3: Production, self-sufficiency and environmental indicators

*Production and self-sufficiency indicators*

The potential area (ha) (Equation 4.1) and the potential production (tones of product) for the entire system (i.e., industrial park) (Equation 4.2) are used as indicators to assess the RTG implementation. The self-sufficiency potential of RTGs is assessed for one product by calculating the total number of people whose demand for the agricultural product is satisfied. This value is accounted by dividing the potential production (total tones of product) by the average consumption of the product in the study area ($kg \cdot person^{-1} \cdot year^{-1}$) (from statistic data) (Equation 4.3).

$$(4.1)\ Short-term\ potential\ area\ (ha) = \sum_{i=0}^{n} Area\ of\ feasible\ rooftop\ (ha)_i$$

$$(4.2)\ Short-term\ potential\ production\ (t) = Short-term\ area(ha) \cdot Crop\ yield\ (\frac{t}{ha})$$

$$(4.3)\ Short-term\ self-sufficiency\ (people) = \frac{Short-term\ potential\ production\ (t)}{Annual\ average\ product\ intake\ (\frac{kg}{person \cdot year})}$$

*Environmental indicators*

Environmental indicators are included in the guide to evaluate the potential benefits of RTG systems (Figure 2). Environmental benefits (Equation 4.4) account those benefits related to the products (e.g., avoided distribution) as well as those benefits related to the building-greenhouse system (e.g., thermal isolation, flows exchange). Environmental benefits are accounted for a timeframe of 1 year and for the entire system under assessment (i.e., industrial park).

$$(4.4)\ Environmental\ benefits\ (EB) = \sum EB_{Product} + \sum EB_{Greenhouse-Building\ system}$$

*Life cycle approach*

The Life Cycle Assessment (LCA) methodology (ISO 2006a; ISO 2006b) is recommended for the quantification of the environmental burdens because it shows an objective quantification of the entire life cycle of the product. At the product level, the functional unit of the assessment is 1 kg of agricultural product. The system boundaries are cradle-to-consumer and include: greenhouse structure and auxiliary equipment (cradle-to-grave, i.e., including maintenance and end-of-life of the structure), agriculture production (consumption of inputs, waste management), distribution (transportation and packaging) and retail (food waste).

The recommended indicators are the avoided GHG emissions (kg $CO_2$ eq.) (Equation 4.5) and the avoided energy consumption (MJ) (Equation 4.6), due to their importance in current environmental policies (e.g., eco-labelling). Therefore, the classification and characterization steps of the life cycle impact assessment follow the Global Warming Potential (GWP) (IPCC 2007)(IPCC, 2007) and Cumulative Energy Demand (CED) (Hischier et al. 2010) methods, respectively.

$$(4.5)\ \text{Avoided GHG emissions (kg CO}_2\text{ eq.)} = Production(t) \cdot Unitary\ benefit\ (\frac{\text{avoided kg CO}_2\text{ eq.}}{kg.product})$$

$$(4.6)\ \text{Avoided energy consumption } (MJ) = Production(t) \cdot Unitary\ benefit\ (\frac{\text{avoided MJ}}{kg.product})$$

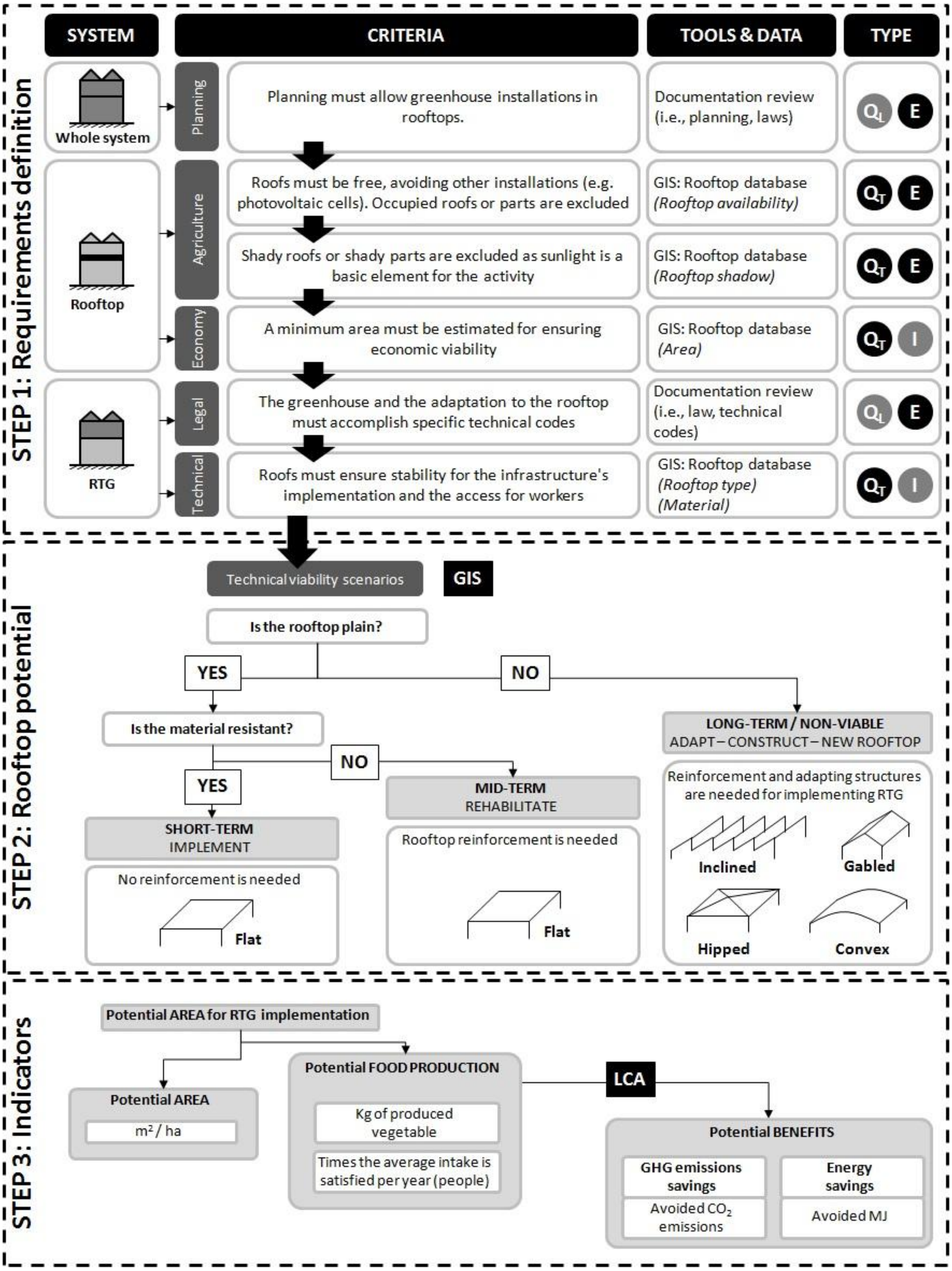


*Figure 4.2. Guide specifications, step by step (Criteria can be Quantitative (QT) or Qualitative (QL), regarding the type of data needed for validation; and External (E) or Internal (I), if the criteria depend on external conditions (e.g., law, third parts) or can be decided internally (e.g., economic outputs and RTG dimension)).*

## 4.3. Methods: Application to a case study

The case study is chosen according to the following criteria: heterogeneity of the building type, proximity to urban areas and to main transportation clusters, and inclusion of a food distribution centre.

### *4.3.1. The Zona Franca park (Barcelona)*

The Zona Franca park in Barcelona (Catalonia, Spain) is chosen as case study. This logistics and industrial park is located in the south of Barcelona, in a strategic area between the port and the airport and it is well connected with the main freight routes (Figure 4.3). Created in 1950s, the current area reaches 600 ha (6% of the municipality of Barcelona) and has become one of the more dynamic industrial areas of Europe, with 300 established companies (Consorci de la Zona Franca de Barcelona 2011). Moreover, the park has been built in different periods and includes buildings of different constructive models.

Besides, Barcelona was identified as a suitable case study for different reasons. The implementation of sustainable strategies and the development of urban food production initiatives have risen in the last few decades. Second, local production is legally protected in periurban areas. The Agricultural Park of Baix Llobregat (Catalonia, Spain) protects the largest agriculture area next to Barcelona. Third, eco-design is already being considered in urban planning, such as the eco-design project of the Vallbona neighbourhood (Barcelona), which included energy efficiency, renewable resources, multi-functionality and rainwater harvesting (Farreny et al. 2011a).

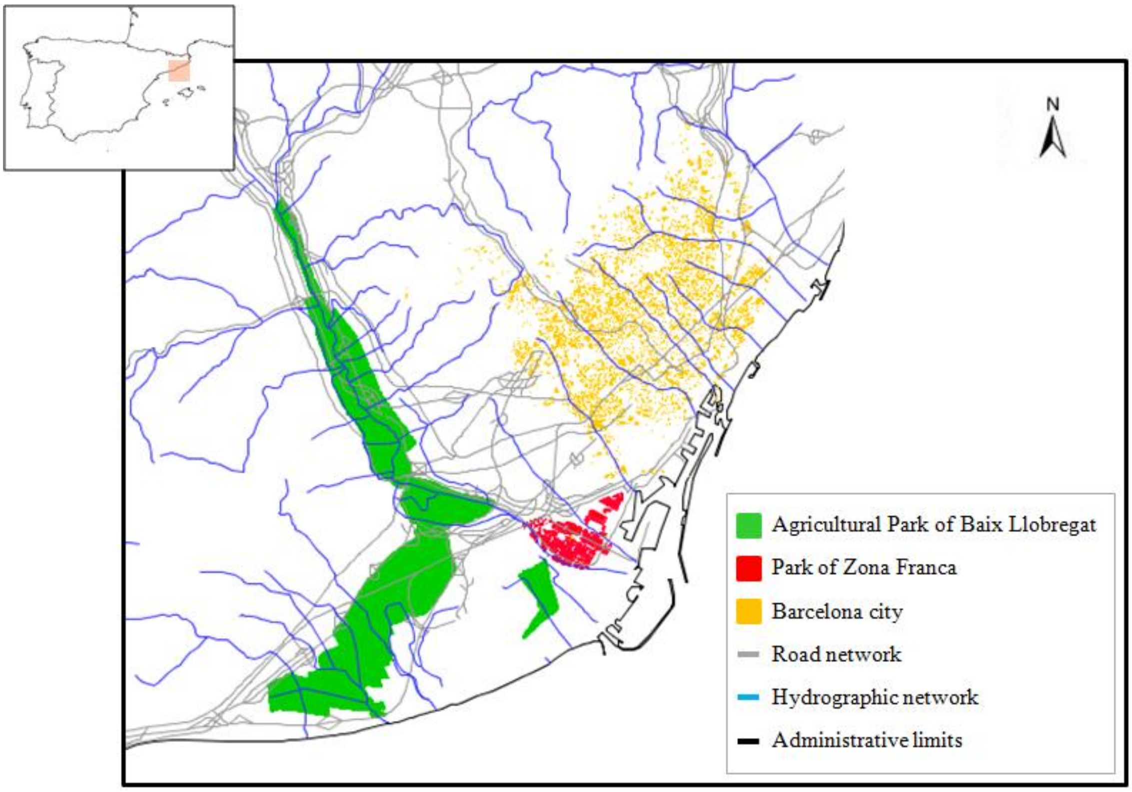


***Figure 4.3.*** *Case study: The Zona Franca park is located in the south of Barcelona (Catalonia, Spain), a former deltaic zone between the port, the airport and the Agricultural Park of Baix Llobregat.*

### 4.3.2. Local data

Specific data are needed for the application of the guide in the case study. To validate the criteria (Step 1), planning documents related to the Zona Franca are checked: General Planning of the Metropolitan Area of Barcelona (Pla General Metropolità) and the Master Plan of the Zona Franca (Pla Parcial de la Zona Franca). According to real experiences, the legal framework in Catalonia which must be considered when implementing RTGs are the Technical Building Code (TBC) (Spanish Government, 2006) and the Act 3/2010 on fire prevention (Spanish Government, 2010). Second, the characteristics of the rooftops are compiled in a GIS layer (Step 2), which was based on the Catalonia orthophotomap, 1:5000 (OF-5 M) v6.0, available online from the Cartographic and Geologic Institute of Catalonia (http://www.icc.cat/vissir3/). The geodesic reference system is the ETRS89 (European Terrestrial Reference System 1989), established as the official reference system by the Royal Decree 1071/2007 (Spanish Government, 2007). Finally, the year of construction and the usage of each building are obtained from the Spanish electronic cadastre (Ministry of Finance and Public Administrations, 2012).

To calculate the production, self-sufficiency and environmental indicators (Step 3), tomato is chosen as agricultural product. Tomato is the second most consumed vegetable in Barcelona, with 20% of the market share, after potatoes (which cannot be produced in through hydroponic RTG systems) (MercaBarna, 2012).

To account the potential production, the crop yield considered for hydroponic tomatoes in an unheated greenhouse in the study area is of 15 $kg \cdot m^{-2}$ (Antón et al., 2005). This is a conservative value, since other studies obtained higher productivity rates (16.5 – 20 $kg \cdot m^{-2}$) (Muñoz et al., 2008). Second, to quantify the self-sufficiency potential in terms of people, the annual average tomato intake considered is of 15.3 $kg \cdot person^{-1} \cdot year^{-1}$, according to Spanish values (MAGRAMA, 2011).

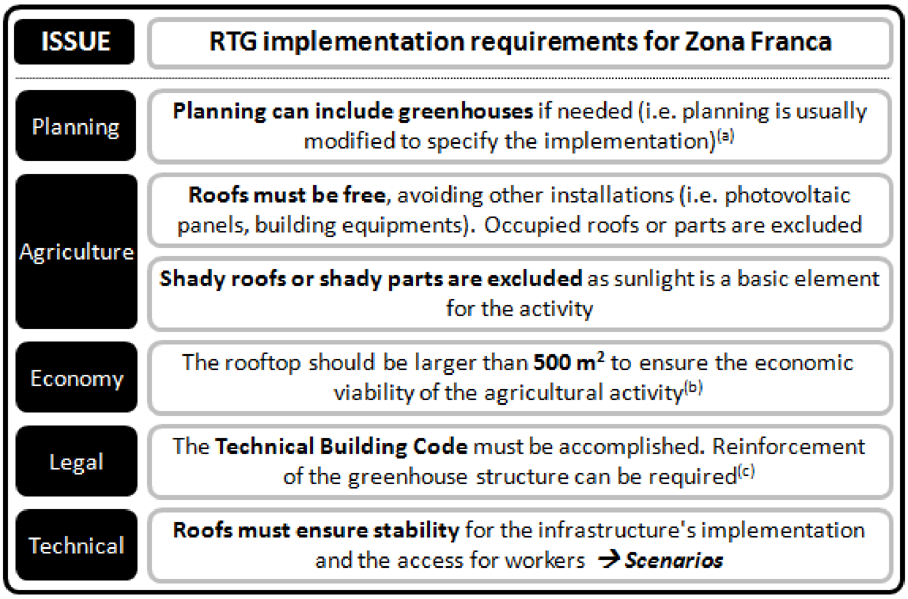
Based on a life cycle approach, the environmental benefits are accounted by comparing the local supply-chain of RTGs to the conventional supply-chain of industrial tomatoes from Almeria where 60% of the tomatoes consumed in Barcelona originate (MercaBarna, 2012). Tomatoes from conventional production are produced in Almeria, transported to Barcelona and sold and consumed in Barcelona. The conventional supply-chain includes three transportation stages: from producer to warehouse, from Almeria (Andalusia, Spain) to Barcelona, and from MercaBarna (placed in the outskirts of Barcelona) to Barcelona city. Furthermore, the loss of product during transportation and retail and the resources consumption in the distribution centre MercaBarna are considered, based on data from Sanyé-Mengual et al. (2013). Therefore, the environmental benefits are those related to the avoided distribution of local production. Sanyé-Mengual et al. (2013) already accounted these environmental benefits. For this study, the environmental savings are adjusted to 435 g of $CO_2$ and 11.8 MJ per kg of tomatoes.

## 4.4. Results of the case study

### 4.4.1. Step 1: Criteria definition in Zona Franca

As abovementioned, three criteria are geographically sensitive (i.e., planning, legal and economy) (Step 1). These three indicators were defined for the study area to obtain the complete multicriteria set to evaluate the Zona Franca (Figure 4). First, the planning and legal documents were revised to assess their flexibility to install greenhouses on rooftops. Furthermore, managers and designers of real RTG projects were interviewed to verify the criteria. Regarding the economic criteria, industrial greenhouses in the nearest agriculture area ranged between 100 and

13,000 $m^2$ in size (Agricultural Park of Baix Llobregat, 2012). According to the panel of experts, larger greenhouses are more economically feasible and a minimum area of 500 $m^2$ was identified as the economic threshold to implement commercial RTGs in the study area.



| **ISSUE** | **RTG implementation requirements for Zona Franca** |
|---|---|
| Planning | **Planning can include greenhouses** if needed (i.e. planning is usually modified to specify the implementation)(a) |
| Agriculture | **Roofs must be free**, avoiding other installations (i.e. photovoltaic panels, building equipments). Occupied roofs or parts are excluded |
| | **Shady roofs or shady parts are excluded** as sunlight is a basic element for the activity |
| Economy | The rooftop should be larger than **500 $m^2$** to ensure the economic viability of the agricultural activity(b) |
| Legal | The **Technical Building Code** must be accomplished. Reinforcement of the greenhouse structure can be required(c) |
| Technical | **Roofs must ensure stability** for the infrastructure's implementation and the access for workers → ***Scenarios*** |

***Figure 4.4.*** *Criteria definition for the case study – Rooftop requirements for implementing RTGs in Zona Franca Park (Barcelona, Spain).*

### *4.4.2. Step 2: Rooftop potential for implementing RTGs in Zona Franca*

According to GIS results, a potential area of 13.06 ha was identified in the Zona Franca park for implementing RTG systems in the short-term, representing 8% of the total roof area (Figures 5 and 6). Within this selection, 51% of the buildings were offices, commercial and services; while 30% were buildings used for industrial activities. The buildings were primarily constructed during the 1970s (Figure 5), when most of the park was developed.

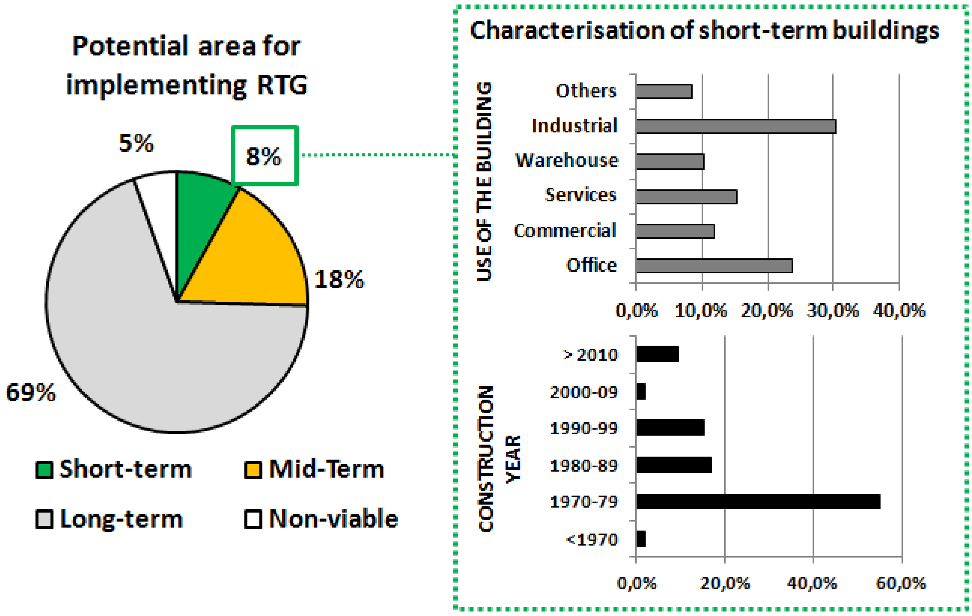


***Figure 4.5.*** *Potential implementation areas for RTGs in Zona Franca park, and characterization of short-term implementation buildings, by building use and year of construction.*

The mid-term implementation considered the potential reinforcement of flat and metals roofs, which included 17% of the roofs (28.6 ha), by increasing the overall potential area to 25%. Finally, the long-term implementation represented 69% of the roofs, which would increase the implementation potential area of RTGs in Zona Franca up to 95% (Figures 5 and 6). These values indicated that the shape of the roof is a more restrictive barrier than the material in industrial and logistics buildings. While the material of the rooftop influenced 17% of the selection (i.e., from the short- to the mid-term), the shape of the roof determined 70% of the implementation (i.e., from the mid- to the long-term).

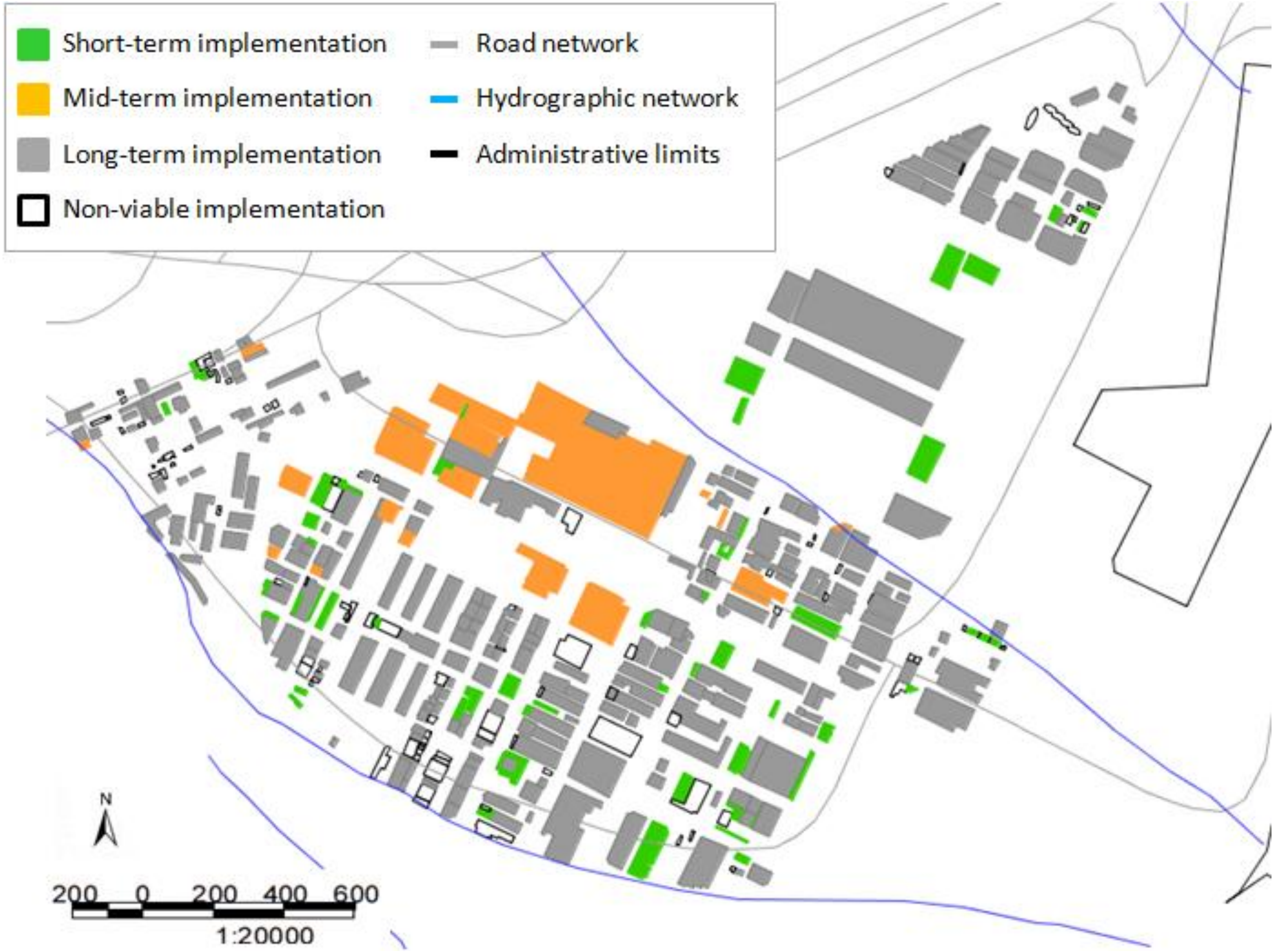


***Figure 4.6.*** *Short-, mid- and long-term implementation of RTGs in the Zona Franca park, according to the established criteria (Scale 1:20.000).*

### 4.4.3. Step 3: Production, self-sufficiency and environmental indicators

A short-term implementation of RTGs in the Zona Franca park (13.06 ha) could produce almost 2,000 t of tomatoes per year, by satisfying the average intake of 130,000 people in the study area. This amount of locally produced tomatoes could substitute industrial tomatoes from other regions of Spain, while avoiding approximately 850 t of $CO_2$ eq. and 23.12 TJ (Table 5).

A rehabilitation strategy (mid-term implementation) could reach a yearly tomato production of 4,000 tones, representing a self-sufficiency potential of 280,000 people. The associated savings could be of 1,863 t $CO_2$ eq. and 50.5 TJ of energy (Table 5). Finally, the adaptation of rooftops (long-term implementation) could boost the annual production up to 17,000 tons of tomatoes (≈1,100,000 people), representing potential savings of 7,373 t $CO_2$ eq. and 200 TJ (Table 5). However, the mid- and long-term scenarios would need an extra structure to meet technical requirements (e.g., reinforcement) and will represent an environmental impact, resulting on shorter environmental savings. Furthermore, these scenarios showed more barriers than the short-term scenario, such as higher investment costs to meet structural requirements.

***Table 4.5.*** *Potential implementation area, tomato production, GHG emissions and energy savings (compared to conventional agricultural products) and self-sufficiency potential (times the yearly average tomato intake is satisfied), by feasibility scenario (short-, mid- and long-term)*

| | | **Economic feasibility scenarios** | | | **Non-feasible rooftops** |
|---|---|---|---|---|---|
| | | **Short-term** | **Mid-term** | **Long-term** | |
| Implementation area | [ha] | 13.06 | 28.55 | 113.00 | 8.82 |
| Tomato production | [t] | 1,959.70 | 4,282.61 | 16,950.16 | - |
| GHG savings | [t $CO_2$ eq.] | 852.47 | 1,862.93$^{(a)}$ | 7,373.32$^{(a)}$ | - |
| Energy savings | [TJ] | 23.12 | 50.53$^{(a)}$ | 200.01$^{(a)}$ | - |
| Self-sufficiency | [people] | 128,085 | 279,909 | 1,107,854 | - |

*(a) Environmental savings are overestimated, as the environmental burdens of reinforcement (mid-term) and adaptive structures (long-term) are not included in the analysis due to lack of data.*

## 4.5. Discussion

### 4.5.1. Guide design and application outcomes

The identification of feasible rooftops for implementing RTGs in industrial and logistics parks required a multicriteria set. The criteria chosen for the guide showed a complete analysis of the requirements, variables and barriers to be considered in RTG projects. Criteria were based on the panel of experts, barriers identified in the literature (Cerón-Palma et al., 2012; Specht et al., 2013) and the experiences of real projects. The selective criteria checklist considered five main issues: planning, agriculture, economy, legal and technical characteristics. As a result, the guide can promote the development of RTG projects by offering a framework to identify potential rooftops. Furthermore, the application of the guide in a case study indicated that the criteria are easily checked through field-work. However, the analysis of a large area or an entire park (i.e., the study area) required the use of GIS to store and work with the data.

On the other hand, several criteria depend on the geographical context, as indicated in the guide. First, legal and planning requirements can be more restrictive (or more flexible) in different countries and even between cities. Second, the economic feasibility relies on the characteristics of the agricultural production (e.g., crop yield, technology). Third, architectural trends and building types, as well as construction materials, are usually different between regions (i.e., due to climatic conditions). Therefore, structural strength can be different and the implementation potential can vary significantly. Finally, environmental policy is also a key aspect. For instance, the promotion of sustainable strategies in urban design can positively affect the implementation of RTGs, making some criteria less strict. Hence, the guide should be applied in different case studies to determine the variability of these criteria.

### *4.5.2. Future criteria and indicators*

In the current version, environmental indicators were calculated to show the positive aspects of implementing RTGs (Step 3). However, in future versions these indicators could be included as selective criteria (Step 1). Therefore, environmental criteria may determine whether an RTG is environmentally friendly enough to be implemented. For example, whether an RTG is environmentally friendly can be defined by a minimum distance from conventional production (km) (e.g., RTG products in Barcelona are environmentally friendly when substituting products that are produced more than 500 km away).

Nevertheless, current research has only quantified the environmental benefits of the distribution stage for RTG systems (Sanyé-Mengual et al., 2013). Then, further research should focus on the quantification of both the environmental impacts and other environmental benefits. On the one hand, the negative burdens of the reinforcement materials for the greenhouse and the building are still unknown, making it difficult to identify the true balance between avoided distribution (environmental savings) and reinforcement costs (negative burdens). Furthermore, the environmental impact of working on rooftops and, thus, the required energy to raise and lower both the agriculture inputs and the produce should be also included in the environmental balance. On the other hand, future studies might quantify the overall environmental benefits of an RTG system, including not only those benefits directly related to the system (i.e., productivity increases, sunlight, energy flow exchanges) but also the indirect ones (i.e., urban benefits such as urban heat island modelling, biodiversity indicators).

Finally, other types of indicators could be included. Future versions of the guide could also work with monitoring indicators to assess the implementation process in a study area. For instance, the percentage of rooftop area where RTGs have been implemented in relation to the total potential area could assess the progress of the implementation of RTGs.

#### RTG productivity and environmental indicators

RTGs can be integrated in the metabolism of buildings, by increasing the efficiency of the agriculture production and the building use. Nevertheless, data is still not available regarding the potential exchange of energy, water and gaseous flows. For the case study, the different type of uses (Figure 6) indicated that several building-greenhouse synergies could be established. Synergies would be related to the exchange of heat (i.e., industrial; 30.4%), the exchange of water flows and the extra isolation provided to the building (i.e., office, warehouse and services; 49.2%).

One of the main benefits of the exchange of flows will be an increase in the crop yield because the greenhouse can be heated by the residual heat of the building. In the case of tomatoes, the productivity could be increased up to 50 kg·m$^{-2}$ in integrated RTGs (i.e., achieving the current Dutch greenhouse productivities) (Montero et al., 2011). When considering a high-yield scenario, the short-term potential would signify a tomato production of 6,500 tons per year (430,000 people), with an associated environmental savings of 2,800 tons of $CO_2$ eq. and 77 TJ of energy.

Additionally, RTGs in Barcelona could reach productivities of 25 kg·m$^{-2}$ by realizing two crop cycles per year (15 kg·m$^{-2}$ in spring and 10 kg·m$^{-2}$ in autumn) (unpublished work, IRTA). Therefore, an isolated RTG (i.e., no exchange of flows) could have two production cycles. The short-term implementation of isolated RTGs could then produce 3,250 tons of tomato (240,000 people), representing an associated savings of 1,500 tons of $CO_2$ eq. and 42 TJ of energy. However, no studies are yet available regarding the agronomic characteristics of RTGs and the potential production values in integrated RTGs.

### Reinforcement and adaptation of the rooftops and environmental implications

As observed, the reinforcement or adaptation of rooftops can boost the RTG implementation potential. First, the reinforcement of flat and metal roofs is a mid-term technical solution that guarantees the structural resistance for installing greenhouses. Second, sloped rooftops need to adapt their shape to become a flat roof. They can be rehabilitated while maintaining their original structure or adapted by means of, for instance, external structures. However, the reinforcement or adaptation of the rooftops would signify a negative environmental impact of RTGs, which have not yet been quantified in the literature.

On the other hand, while the adaptation of existing buildings may focus on the shape and resistance of the rooftop, the design of new buildings may pay attention to the whole system. Therefore, a new design may ensure the requirements for implementing RTGs (e.g., sunlight, roof type) at the same time that the environmental impact of the entire structure is minimized (e.g., local materials, environmentally-friendly materials). In this sense, the consideration of RTGs in the design stage of buildings will optimize the resources use in both systems.

### Trends in the technical and economically feasibility for implementing RTG

According to the technical feasibility criteria, only flat and concrete rooftops were considered to be feasible in the short-term. Currently, industrial and logistics parks are dominated by metal roofs (i.e., 88% for the case study). However, an assessment of the year of construction noted that new buildings (built after 2000) are more resistant than old buildings, since the current legal framework requires that rooftops must be prepared for a possible installation of photovoltaic cells. Therefore, managers and urban planners can reduce the barriers for implementing RTGs, e.g., by including technical requirements in the construction normative. Furthermore, RTGs can take advantage of popular sustainable technologies (i.e., solar energy) that are competing for the same space: rooftop surfaces. RTG promoters can follow the implementation procedures and legal framework adaptation processes that were made for these technologies (e.g., the solar ordinance of the town hall of Barcelona).

Due to the globalization process and the market trends, the price of agricultural products is regulated by the own market. Thus, a high-tech system for urban agriculture might not seem economically feasible due to the initial cost of the greenhouse structure. Specifically, the greenhouse structure and the operation costs can represent higher costs than in conventional agriculture (even more when comparing to open-field agriculture). However, economic benefits can overcome these costs, making the cost-benefit balance positive. First, in local production systems distribution costs are minimized or avoided, providing certain benefits to the economic activity. Second, soil-less culture systems are more efficient than conventional ones, reducing the consumption of water, energy and fertilizers. Third, the use of rooftops can minimize the cost of land use (in contrast to rental contracts for agriculture soil). Finally, the integration of energy flows between the greenhouse and the building is expected to increase the productivity without enlarging the resources consumption. In this case, marginal costs will be reduced (as well as the energy requirements for the acclimatization of the building).

In fact, current commercial RTGs have succeeded and most of them are planning new RTGs to increase the variety of products. Particularly, products from RTGs are already in groceries of the United States, with lower prices than other ecological options (i.e., organic products) (http://gothamgreens.com/). Furthermore, consumers of ecological agricultural products are increasing, citing local production as one of the main criteria for their selection (Tobler et al., 2011). Therefore, the minimum area for an RTG to be economically feasible can be smaller if RTG products have an existing presence in the market and economic costs are reduced.

Finally, RTGs can follow different exploitation or use models. As shown in this guide, commercial RTGs are expected to be large scale in order to achieve profitable margins considering the economy of scale (e.g., in this guide we have estimated that a minimum size should be of 500m$^2$). However, RTGs can also be implemented in residential areas (both private and public buildings) to contribute to the food self-sufficiency of specific stakeholders (e.g., neighbourhood's coops, associations, food coops, community gardening associations, individual citizens). Finally, RTGs can specifically offer social functions such as for educational purposes (e.g., schools, universities, foundations, museums) or for leisure and health (e.g., hospitals, day-care centres). In residential and social models, economic issues are less important than for commercial RTGs, as other aims are prevalent (e.g., social benefits, community engagement, and education) (Mok et al., 2013). In this sense, for other purposes than commercial, economic criteria can be excluded of the guide.

### Compatibility to other uses

Detractors of rooftop farming commonly identify the occupation of the rooftops as a threat to other sustainable systems, such as photovoltaic (PV) production. Nevertheless, RTGs can be compatible to other uses by sharing part of the rooftop, such as the RTG of Gotham greens which is combined with PV production, or by integrating sustainable systems in the RTG design, e.g. rainwater harvesting (RWH). At the industrial park level, sustainable systems can occupy different rooftops according to their requirements. For example, while RTGs must be implemented on flat and concrete rooftops, PV production and RWH can be implemented on inclined rooftops where they obtain better results (e.g., facing south). Therefore, a planning of the rooftop usage could lead to a multifunctional use of the different rooftops of an industrial park (e.g., RWH, PV production, RTG, green roof).

To contextualize, the environmental benefits per area of implementing RTGs were compared to the potential PV production. For the case study, the annual PV production could be of 168kWh·m$^{-2}$ (calculated on PVGIS (JRC, 2014)). This production could substitute conventional electricity from the Spanish grid, which for the year 2013 (REE, 2013) had an environmental profile of 321 g $CO_2$ eq.·kWh$^{-1}$. Considering that the PV cells production has an environmental impact of 63.8 g $CO_2$ eq.·kWh$^{-1}$ (average of reviewed studies in Sumper et al., 2012), the environmental balance would result on savings of 43.21 kg $CO_2$ eq.·m$^{-2}$. According to previous results, RTGs would save 6.5 kg $CO_2$ eq.·m$^{-2}$ (see Table 5), representing 15% of the PV production. However, the deployment of PV production depends on the energy policy of the region and it dramatically slowed down in the study area since the Spanish renewable energy policy of 2008. The new regulatory framework implemented less favourable Feed-in tariffs (FIT) for the producers and started to limit the PV growth by means of a capacity quota (Del Río and Mir-Artigues, 2012; Solangi et al., 2011). As a result, although PV production offers larger environmental benefits, the policy changes have made PV production less attractive from the economic perspective.

## 4.6. Conclusions

The guide designed in this study was an effective tool for determining the feasibility to implement RTGs in a study area and to quantify the potential area and indicators (i.e., production, self-sufficiency, environmental). Furthermore, the guide can help stakeholders in the decision-making process of implementing RTGs not only in a single building but also in an entire system (e.g., industrial park). Particularly, the guide can be a useful tool in the planning of new urban areas, when agriculture and food production are considered in their design.

The guide identified the main criteria for selecting roofs when implementing RTGs. In particular, criteria identified the rooftops that are both technical and economically feasible. Furthermore, the barriers that real RTG projects have found were considered. However, for large areas, GIS tools are needed to manage the necessary data. Finally, the proposed indicators show complementary information of the potential production, self-sufficiency and environmental benefits of the implementation of RTGs.

Regarding the environmental quantification of RTGs, further research for quantifying both potential benefits and impacts should be performed to complete the environmental balance of RTGs to avoid an overestimation of the environmental benefits. Finally, the criteria can be different depending on the geographical context (either country or city). In this sense, the guide should be applied in different study areas to observe the potential variability of the criteria and of the potential implementation of RTGs (e.g., architectural design in North Europe can enhance RTG potential).

The implementation of RTGs in industrial and logistics parks showed a great potential, since their design includes large roofs. However, only 8% of the roofs of the Zona Franca park resulted feasible for a short-term implementation of RTGs, due to the large presence of sloped or metal roofs (which would need to be reinforced). In this sense, if metal roofs were reinforced to ensure stability (mid-term implementation) the percentage of implementation would be increased to 25%. Besides, if adaptive structures (long-term implementation) were designed, 95% of the roofs could be used for RTG purposes. Nevertheless, the reinforcement or adaptive structures for roofs have not yet been designed, and their environmental profile is unknown. Finally, environmental savings of a short-term implementation of RTGs in Zona Franca could represent savings of approximately 850 t of $CO_2$ eq. and 23.12 TJ of energy. However, the environmental performance of RTGs in real cases has not been analyzed. Therefore, both positive and negative environmental burdens have not been considered: further benefits of the relationship between the RTG and the building, variations of the greenhouse structure and possible roof reinforcement must be researched.

# Chapter 5

## Urban horticulture in retail parks:

### *Environmental assessment of the potential implementation of Rooftop Greenhouses (RTGs) in European and South American cities*

Picture: *Lettuce production in the RTG-Lab (Bellaterra, Spain)*
*(©Esther Sanyé-Mengual)*

# Chapter 5

This chapter is based on the journal paper:

> Sanyé-Mengual E, Martínez-Blanco J, Finkbeiner M, Cerdà M, Camargo A, Ometto AR, Velásquez LS, Villada G, Niza S, Pina A, Ferreira G, Oliver-Solà J, Montero JI, Rieradevall J. Urban horticulture in retail parks: environmental assessment of the potential implementation of Rooftop Greenhouses (RTGs) in European and South American cities. *Journal of Cleaner Production* (under review)

## Abstract

Urban agriculture (UA) experiences spread over the world as a response to the population growth and the search of new forms of local production. Recently, UA is also being integrated in and on buildings, such as Rooftop Greenhouses (RTGs) which are greenhouses implemented on rooftops for food production. Current RTG projects are greenhouses isolated from the building where they are placed. However, integrated RTGs (i-RTGs) are expected to integrate their flows (energy, water, $CO_2$) into the metabolism of the building, based on an industrial ecology approach. Assessing the implementation of RTGs in retail parks might enable the identification of opportunities (regarding food, energy and water vectors) of these systems to define their relevance in future sustainable planning and UA policies. Nevertheless, although retail parks have expanded around the world, the implementation of RTGs could have different results according mainly to climatic conditions (e.g., energy requirements for greenhouse food production).

This paper performs a multi-national assessment to provide a more comprehensive vision of the potential of RTGs in retail parks. A GIS-LCA method has been applied to calculate both potential and benefits of implementing RTGs, in terms of area, production, self-supply, environmental savings and improvement of rainwater harvesting. Eight case studies in Europe and South America were analysed regarding the potential implementation of isolated RTGs and i-RTGs (energy exchange). Results showed that retail parks have a large potential for the implementation of RTG in the short-term (53 – 98 % of the rooftops are feasible). However, architecture constraints are limiting factors, such as for Colombia where roof material limited the potential to 11%. The implementation of isolated RTGs obtained large values of yield (31 to 234 tonnes of tomato per ha), $CO_2$ savings (16 to 112 tonnes of $CO_2$ eq. per ha) and self-supply (380 – 21,500 people per ha; 3.5-60% of local tomato demand). However, the potential implementation of integrated i-RTGs could boost the food production and the potential self-supply (up to 1.8 times) as well as the environmental benefits from local production (up to 2.5 times higher). Moreover, the resulting modification of the rooftop shape from implementing RTGs could increase the rainwater harvesting (RWH) potential between 114 and 145%, which used in the crops would lead to a water crop self-sufficiency.

Keywords: Local production, Urban Agriculture, Ecoinnovation, Industrial ecology, Food security

## 5.1. Introduction

Urban agriculture (UA) is a field of growing interest as may be witnessed by an expansion of local food production experiences (Taylor and Taylor Lovell 2012; Mok et al. 2013). This trend reacts not only to urban population growth around the world (UN-Habitat 2013b) and the consequent boost of urban food demand, but also to an increasing concern in the food-related environmental impacts (Howe and Wheeler 1999; Garnett 2013). Current UA activities are either commercial or non-profit (e.g., self-supply) and have been occupying different spaces of urban areas: community farms, community gardens, backyard farming, public gardens and vacant lands (Cohen et al. 2012; Mok et al. 2013). In its multiple forms, UA positively contributes to the environmental, economic and social sustainability of cities (e.g., Despommier, 2011).

Beyond traditional UA forms, new UA projects are linked to the integration of agriculture into buildings (Lee-Smith 2009), which has been defined in the literature as ZFarming (Zero Acreage Farming) (Specht et al. 2014) or Skyfarming (Germer et al. 2011), for instance. Building-Integrated UA forms vary from unprotected extensive farming (e.g., community rooftop farming) to environment-controlled horticulture under greenhouses (e.g., heated rooftop greenhouses). This integration can be displayed in a variety of manners, like Vertical Farming, Rooftop Greenhouses, and somehow related Green Roofs. Vertical Farming (VF) consists of "farming inside tall buildings within the cityscape" (Despommier 2008; Despommier 2009; Despommier 2010; Despommier 2011). Green Roofs (GR) are roofs that are purposely fitted or cultivated with vegetation that are particularly used as urban drainage systems (White and Alarcon 2009), thermal and acoustic insulation and eventually also for horticultural production (Magill et al. 2011).

Notwithstanding, current commercial Building-Integrated UA forms are mainly Rooftop Greenhouses (RTGs). RTGs are greenhouses located on the top of buildings for food production. Nowadays there are a few commercial RTGs that are running their businesses, for instance in North America, such as Gotham Greens in Brooklyn (New York, USA), The Vinegar Factory in Manhattan (New York, USA) (Eli Zabar 2013), and Lufa Farms in Montreal (Canada) (Lufa Farms 2013). These experiences have built RTGs that ranges in size from 830 $m^2$ to 2,900 $m^2$. They produce different vegetables (e.g., tomatoes, lettuce, peppers, eggplants, herbs) which are sold through their own shops, specialized supermarkets or Community Supported Agriculture (CSA) systems (Resh 2012).

### *5.1.1. An industrial ecology approach: integrated Rooftop Greenhouses (i-RTGs)*

Current RTGs are usually segregated structures from the rest of the building (i.e., isolated RTGs). However, RTGs could integrate their flows in the metabolism of the building. These integrated RTGs (i-RTGs) may become not only a food production system in urban areas but also provide other services, while integrating the flows between the greenhouse and the building (Cerón-Palma et al., 2012). In i-RTGs, energy, water and gas flows could be exchanged through a symbiotic metabolism among the two spaces (the greenhouse and the building) thereby optimizing the resource requirements of both functions (Figure 5.1):

- Energy flows: Energy consumption related to food production (i.e., greenhouse) and building use could be lowered by exchanging waste heat between the systems (Cerón-Palma et al. 2011; Cerón-Palma 2012). This would contribute namely to reduce the energy consumption of the building sector, which is a great consumer of energy resources in the use phase (e.g., 27% in Europe (EUROSTAT 2010)).

- Water flows: Water (rainwater and grey water collected in the surfaces of the building) can be exchanged thereby improving the management for different uses (e.g. watering in the RTG, toilet flushing in the building, and cooling in both).
- Gas flows: Greenhouse yields could profit from $CO_2$ produced in the building (i.e., by its occupants), while releasing low-$CO_2$ airflow. Moreover, the optimization of agriculture yields (through $CO_2$ exchange) in i-RTGs may occur without increasing externalities, while contributing to food security as urged by FAO (2013).

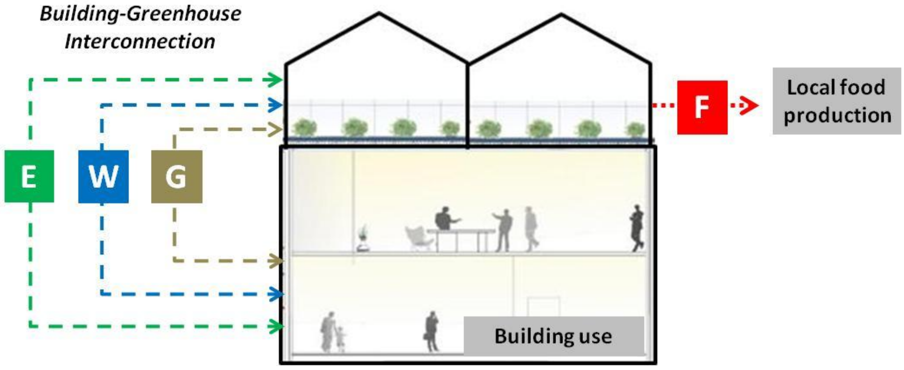


***Figure 5.1.*** *Integrated Rooftop Greenhouses (i-RTGs) concept: energy [E], water [W] and gases [G] exchange to optimize both the function of the building (building use) and the greenhouse (local food production [F]). Based on Cerón-Palma et al. (2012).*

Recent research on both isolated and integrated RTGs has focused on the identification of barriers and opportunities of these systems (Cerón-Palma et al. 2012), quantifying the potential environmental benefits related to the avoided distribution of vegetables (Sanyé-Mengual et al. 2013) and proposing a method to quantify the potential implementation of RTGs in industrial and logistic parks and assessing their environmental benefits (Sanyé-Mengual et al. 2015a). Particularly for i-RTGs, Cerón-Palma (2012) realized a first theoretical analysis of the exchange of the energy flow between the building and the greenhouse, based on energy simulation software. The residual heat from the greenhouse during the day was redirected to the building to reduce the energy demand for heating indoor spaces. The case study was an office building in the Mediterranean area and obtained positive results thereby reducing heating demand by 79% in the building on an ideal winter day.

### *5.1.2. Retail parks as potential location for RTGs*

Retail parks are a type of service park defined as "a group of many single-storey retail units, which typically host a range of chain stores, including supermarkets and clothes or footwear, electrical and Do It Yourself (DIY) superstores, with abundant free parking and proximity to major roads" (Farreny et al. 2008). Environmental research on these systems has focused on the quantification of energy flows (Farreny et al. 2008; Park and Hong 2011; Sanyé et al. 2012) and on the use of the rooftops for obtaining renewable resources, such as rainwater (Farreny et al. 2013). However, no previous studies were found assessing the potential of application and the environmental performance of RTGs in service parks.

Retail parks may be suitable for implementing RTGs, since:

- They usually have buildings with large rooftops, are placed near to big food-consumption areas (i.e., cities), and have good communication infrastructures with these (proximity to major roads).
- They normally include supermarkets where local products (also known as “km.0-products”) from RTGs could be sold, offering potential environmental advantages from the avoided logistics (Sanyé-Mengual et al. 2013).
- Retail parks are urban areas that usually produce high amounts of storm water runoff (Farreny et al. 2013) which could be used for food production in RTGs by using rainwater harvesting (RWH) systems.
- Furthermore, RTGs may increase RWH efficiency by converting flat roofs into leaning ones, according to the run-off coefficients in Farreny et al. (2011). These authors suggest that the modification of the rooftop shape can positively modify the run-off coefficient and increase RWH.
- Finally, RTGs could take advantage of the waste heat from retail buildings in an industrial ecology perspective (i-RTGs).

In this sense, assessing the implementation of RTGs in retail parks might enable the identification of potentialities (regarding food, energy and water vectors) for these systems and define their importance for future sustainable planning and urban agriculture policies. Although retail parks have expanded around the world, existing up to 9000 only in Europe (RegioData 2014), the implementation of RTGs may expectedly have different results in different geographic areas. Architectural trends (e.g., rooftop type) or climatic conditions (e.g., energy requirements for greenhouse food production) can affect the implementation potential of RTGs, not mentioning different cultural practices. Therefore, a multi-national assessment could provide a more comprehensive vision of the potential of RTGs and their resulting benefits.

### *5.1.3. Objectives*

This paper aims to assess the potential implementation of i-RTGs in retail parks as an industrial ecology strategy to improve the environmental performance of both the urban food system and the retail park. The analysis includes eight case studies in seven cities of Europe and South America: Barcelona in Spain (two different case studies), Lisbon in Portugal, Utrecht and Rotterdam in the Netherlands, Berlin in Germany, Manizales in Colombia and São Carlos in Brazil. The guide for assessing the implementation of RTGs in logistic parks developed by (Sanyé-Mengual et al. 2015a) is revisited and applied to the new context of retail parks (Appendix 1.1). Besides, new indicators are assessed to better evaluate food self-supply and the improvement for RWH systems.

For this purpose, the paper addresses the following research questions in each of the locations:

- Which is the potential for implementation, food production, environmental benefits and contribution to food self-supply of RTGs in retail parks? How much could i-RTGs increase these figures?
- How much can RTGs improve the RWH potential of retail parks? Could RTGs be water self-sufficient from rainwater sources in the retail parks?
- What are the geographic preferences for implementing RTGs in the study areas assessed?
- Which are the limiting factors for the implementation of RTGs, their production and benefits? How do architecture and design determine the RTG potential?

## 5.2. Methods

In this section, the case studies and the method used for assessing the implementation potential of RTGs are explained highlighting the validation, adaptation and improvement of previous research on the field.

### *5.2.1. Study areas*

The eight retail parks under assessment are placed in seven different study areas (i.e., cities). The five European cities are located in Spain, Portugal, The Netherlands and Germany, while two cities in Colombia and Brazil were chosen for South America (Table 5.1 and Figure 5.3). The selection was performed to assure the following criteria: (a) Representativeness of warm and cold climate conditions and different rainfall patterns, (b) Representativeness of urbanization patterns (i.e., urban population and density), (c) Representativeness of greenhouse production systems (e.g., heated, unheated), (d) Large presence of retail parks in the urban areas of the country, (e) Potential differences in retail park design (e.g., compact and diffuse parks), and (f) Existence in the country of Rooftop Greenhouse (RTGs) projects as commercial or research initiatives.

As a result, the paper assessed those study areas in Europe where major production of horticulture under greenhouse already takes place (The Netherlands and Spain) and those that currently need to import vegetables (Portugal and Germany) where RTGs might increase their national production. Two more study areas are included in emerging countries (Colombia and Brazil) where new technologies might contribute to their economic development and face social inequalities (e.g., food access). Table 5.1 describes climatologic and socio-economic data for the case studies.

The type of climate of the study areas is mostly warm though with variants from Mediterranean, to Atlantic and Subtropical. Average temperatures of the cities at stake vary considerably ranging from 9.6°C in Berlin to 21.5°C in São Carlos and precipitation ranges from more than 1,495 mm per year in South American cities to a minimum of 571 mm in Berlin. Population density also varies considerably, from a maximum of 160 habitants per hectare in Barcelona to a minimum of 30 habitants per hectare in Rotterdam. Interestingly, as a proxy of the importance of agriculture in the countries, the contribution of agriculture to GDP in the analysed countries ranged from 1-3% in European countries to 6-7% in South American ones.

#### Retail parks

A retail park stands for the aforementioned definition by Farreny et al. (2008). Suitability of case studies of retail parks in, or nearby, selected cities was assessed according to the following criteria: (a) Compliance to the previous definition, (b) Representativeness of the retail parks in the geographic areas: (b1) Extension between 15,000 and 500,000 m$^2$, (b2) Maximum distance to the city centre of 20 km; (c) Presence of supermarkets (as a proxy of the potential RTG products demand), and (f) Availability of GIS data (i.e., aerial images).

Table 5.2 displays the characteristics of the eight retail parks selected. Two case studies were chosen for Spain and The Netherlands areas to show different design patterns of retail parks (e.g., compact-diffuse). Retail parks are either in periurban or urban areas with an extension between 1.6 and 43.2 ha (average: 22.6 ha). Also, the retail parks examined can be split into compact (built area > 45% total area) and diffuse parks. Land use distribution of the retail parks and design patterns are represented in Appendix 1.2. The description of the work developed to produce these maps is described in section 5.2.2.

***Table 5.1.*** *Climatic and socio-demographic conditions, by study area (country and municipality level).*

| Country | Spain (ES) | Portugal (PT) | The Netherlands (NL) | | Germany (DE) | Colombia (CL) | Brazil (BR) |
|---|---|---|---|---|---|---|---|
| **Agriculture contribution to national GDP (%)(a)** | 3 | 2 | 2 | | 1 | 7 | 6 |
| Municipality | **Barcelona (BCN)** | **Lisbon** | **Utrecht** | **Rotterdam** | **Berlin** | **Manizales** | **São Carlos** |
| *Climatic conditions* | | | | | | | |
| **Type of clime(b)** | Warm temperate Mediterranean | Warm temperate Mediterranean | Warm temperate Atlantic | | Warm temperate continental | Tropical equatorial | Warm subtropical |
| **Average temperature (°C)** | 16.2 | 16.0 | 9.8 | 10.0 | 9.6 | 13.0 | 21.5 |
| **Annual precipitation (mm)** | 587 | 726 | 900 | 802 | 571 | 1,495 | 1,360 |
| *Socio-demographic* | | | | | | | |
| **Population (2013) (inhabitants)** | 1,594,412 | 547,631 | 316,448 | 617,347 | 3,521,000 | 420,525 | 218,201 |
| **Density ($\text{inhab·ha}^{-1}$)** | 159.9 | 64.6 | 32.6 | 29.9 | 39.2 | 91.0 | 33.0 |
| **GDP/inhabitant (€)** | 26,600(c) | 22,700(c) | 41,900(c) | 35,300(c) | 28,900(c) | 5,738(d) | 8,845(d) |

*(a) World Bank (2012a); (b)Type of clime corresponds to the updated Köppen classification* (Peel et al. 2007); *(c)EUROSTAT (2013); (d) World Bank (2012b)*

***Table 5.2.*** *Characteristics of the selected retail parks and land use distribution, per case study.*

| ***Retail park*** | **ES** | | **PT** | **NL** | | **DE** | **CL** | **BR** | **Average** |
|---|---|---|---|---|---|---|---|---|---|
| | **BCN-Sant Boi** | **BCN-Montigalà** | **Lisbon-Alfragide** | **Utrecht** | **Rotterdam** | **Berlin** | **Manizales** | **São Carlos** | |
| Periurban (P) or urban (U) | P | P | P | U | U | P | U | P | - |
| Extension ($m^2$) | 252,807 | 202,684 | 350,631 | 132,929 | 170,125 | 432,491 | 15,832 | 252,807 | *226,288* |
| Distance to city (km) | 9.3 | 8.2 | 8.5 | 4.5 | 1.4 | 20.0 | 0.5 | 9.3 | *8.0* |
| Compact (C) or diffuse (D) | D | C | D | C | C | D | D | D | - |
| ***Land use characterization*** | | | | | | | | | |
| Buildings (%) | 30.0 | 48.4 | 30.7 | 50.6 | 50.2 | 30.3 | 37.9 | 30.0 | *39.0* |
| Parking (%) | 31.3 | - | 20.2 | 7.1 | 9.7 | 23.2 | 11.1 | 40.0 | *20.0* |
| Gardens (%) | 8.4 | - | 23.8 | 6.0 | 8.3 | 13.9 | 11.9 | 10.0 | *12.0* |
| Logistics spaces (%) | 6.9 | 1.3 | 2.7 | 3.5 | - | 26.5 | 1.1 | 6.0 | *7.0* |
| Roads and paths (%) | 14.7 | 50.3 | 22.7 | 30.4 | 31.9 | 3.0 | 38.0 | 14.0 | *26.0* |
| Park growth (%) | 8.6 | - | - | 2.5 | - | 3.1 | - | - | *5.0* |

### *5.2.2. Assessing the potential for implementing RTGs in the selected retail parks*

This paper follows the method defined by Sanyé-Mengual et al. (2014), which was developed to determine the short-term potential implementation of RTGs in industrial and logistic parks. The short-term potential refers to those rooftops where RTGs might be implemented with no need of structural reinforcement or rehabilitation (e.g., non-flat roofs would need to be modified and their potential would be long-term). Appendix 1.1 details the method that can be summarized in the following steps:

- Step 1: Criteria definition. A multi-criteria set is defined for the identification of the rooftops, where RTGs can be implemented. Criteria combine requirements from the technical, economic, legal, planning and agriculture perspectives.
- Step 2: Rooftop potential quantification. By means of Geographic Information Systems (GIS), data needed to check the criteria from Step 1 are collected for each rooftop. Data include rooftop type, rooftop material, availability, shadow and area. Those rooftops that fulfil the requirements are then identified as short-term potential rooftops for implementing RTGs.
- Step 3: Production, self-supply and environmental indicators. To assess the implementation of RTGs, three indicators are calculated. First, total RTG production is accounted for. Second, this potential production is related to consumption in the study area, in order to observe the potential self-supply. For a certain vegetable, the total RTG production of the retail park is compared with the yearly average intake. The indicator measures how the potential implementation of RTGs can satisfy the demand of some citizens of the study area. Second, the potential environmental savings associated to the avoided distribution of non-local products is accounted for as greenhouse gas (GHG) emissions savings (kg $CO_2$ eq.) and energy savings (MJ).

In this paper, new indicators are proposed to complement the ones described in Sanyé-Mengual et al. (2014) for this purpose. Section 2.2.2 describes the modifications of the Step 3 of this methodological framework.

#### Application of the method

*(a) Validation of the criteria for the study areas (Step 1)*

Some of the criteria of Step 1 can be defined as standard since the implementation of a RTG must be done on a flat and resistant roof (technical criteria of shape and material), free of other installation (available space) and on a non-shadowed roof to avoid crop yield decrease. Nevertheless, some other criteria may be country-sensitive in relation to planning, legal and economic context. Therefore, we checked the consistency of the criteria for each study area and explored the possibility of adding new criteria. However, additional criteria were not considered necessary. For carrying out a systematic validation, planning, legal and economic criteria were validated for each case following a specific flowchart and consulting reference documentation (e.g., law documents) (see Appendix 1.3).

*(b) GIS data and retail parks characterisation (Step 2)*

A retail park geo-database was created for each case study to enclose the data needed to verify the requirements for implementing RTGs. Besides, the land-uses observed in each retail park were compiled and classified as follows: buildings, gardens, roads and paths, logistic spaces, parking and areas under construction (Appendix 1.2). This parameter was used to characterise differences and similarities between retail parks (additionally to the information on Table 5.2) and the possible effect of morphology and design aspects (e.g., compact vs. diffuse) on the potential implementation of RTGs in retail parks.

### Calculation of production, self-supply and environmental indicators (Step 3)

*(a) RTG scenarios*

Two scenarios were considered for the implementation of RTGs to compare the implementation of isolated RTGs (Scenario A) and integrated RTGs (i-RTGs) (Scenario B). The comparison quantified the effects of applying an industrial ecology approach in i-RTGs. Hypothetically, i-RTGs will result into more efficient crops than isolated RTGs since the integration of energy, water and $CO_2$ flows increase the resource efficiency (as detailed in Section 1.1). This study focuses on the energy flow since the introduction of waste heat from the building to the greenhouse can improve the crop yield or reduce the energy demand from conventional sources, depending on the study area and greenhouse technology.

Table 5.3 compiles the characteristics of each scenario and the different effects on crops in warm and cold climates. As no experimental data is still available on the effects of energy exchange in i-RTGs or similar systems, the current study analysed integrated RTGs (Scenario B) based on the hypothetical effects. As a result, the potential benefits of i-RTGs were assessed as a sensitivity parameter, considering from a 0% to 100% effect on increasing the crop yield (warm climates) or 0% to 100% effect on reducing the consumption of conventional energy (cold climates).

***Table 5.3.*** *Characteristics of the flow exchange and crop outputs, by scenario.*

| Scenario | Flows exchange | Crop characteristics |
|---|---|---|
| Scenario A:<br>**Isolated RTGs** | RTGs do not exchange flows with the building | The parameters of the horticultural production are considered to be the same as of conventional greenhouses |
| Scenario B:<br>**Integrated RTGs** | RTGs exchange the energy flow with the building where they are built on | **Warm climates:** Crop yield increase. The waste heat from the building acts as source of energy to increase the yield, while avoiding extra energy consumption. Crop yields are expected to increase up to current Dutch productivity (56.5 kg·m$^{-2}$), which is considered the maximum in this assessment. |
| | | **Cold climates:** Reduction in conventional energy consumption. The waste heat from the building substitutes conventional energy used in heated greenhouses, while reducing the crop energy consumption. The maximum effect of heat exchange is assumed to substitute the total conventional energy demand of the system. |

*(b) Production and self-supply indicators*

For this study, tomato was chosen since it can be cultivated in all the selected study areas and due to its importance in the different food markets. According to FAOSTAT (FAO 2013c), tomato is the most produced vegetable in the countries under assessment, apart from Germany, where it is the third crop (after carrots and lettuce). The total production of tomatoes was calculated for the short-term potential of RTGs. The crop yield was different for each scenario and study area (Table 5.4). Scenario A (isolated RTGs) used the reference crop yield of conventional greenhouses in the study area and data was obtained from the literature. However, scenario B (i-RTGs) considers the effects of the waste heat exchange which depend on the study area (Table

5.3). For cold climates, waste heat is used to maintain high crop yields while reducing energy inputs and, thus, crop yield values are the same as in scenario A. On the other hand, waste heat on warm climates is supposed to increase crop yields. Scenario B shows the potential crop yield increase as a sensitivity variable that ranges from the reference crop yield of the study area (0% effect) to the potential maximum crop yield (100% effect) (Table 5.4).

The self-supply indicators calculate the potential effect of the RTG production in the local consumption of tomato. Equation 5.1 shows the self-supply indicator defined in Sanyé-Mengual et al. (2014), which expresses the number of times the annual average intake is satisfied (in terms of people). A new self-supply indicator was added. Equation 5.2 calculates the ratio between the local production provided by the RTGs and the local consumption (in terms of percentage). Crop yield and average tomato intake are reported for each case study in Table 5.4.

$$(5.1)\ Self - supply\ potential\ (people) = \frac{Production\ (kg \cdot year^{-1})}{Average\ intake\ (kg \cdot person^{-1} \cdot year^{-1})}$$

$$(5.2)\ Self - supply\ degree\ (\%) = \frac{Production\ per\ area\ (kg \cdot year^{-1} \cdot m^{-2})}{Average\ intake\ (kg \cdot person^{-1} \cdot year^{-1}) \cdot Inhabitant\ (people)}$$

***Table 5.4.*** *Input data to calculate production and self-supply indicators, by case study and country*

| | **ES** | | **PT** | **NL** | | **DE** | **CL** | **BR** |
|---|---|---|---|---|---|---|---|---|
| | **BCN-Sant Boi** | **BCN-Montigalà** | **Lisbon** | **Utrecht** | **Rotterdam** | **Berlin** | **Manizales** | **São Carlos** |
| Tomato crop yield (Scenario A) (kg·m$^{-2}$·year$^{-1}$) | 16.5[(a)] | 16.5[(a)] | 20.0[(b)] | 56.5[(a)] | 56.5[(a)] | 56.5[(a)] | 15.7[(c)] | 18.1[(d)] |
| Tomato crop yield (Scenario B) (kg·m$^{-2}$·year$^{-1}$) | 16.5 to 56.5 | 16.5 to 56.5 | 20.0 to 56.5 | 56.5[(a)] | 56.5[(a)] | 56.5[(a)] | 15.7 to 56.5 | 18.1 to 56.5 |
| Average tomato intake (kg·person$^{-1}$·year$^{-1}$) | 17.2[(e)] | 17.2[(e)] | 14.0[(f)] | 10.9[(g)] | 10.9[(g)] | 20.6[(h)] | 11.6[(g)] | 10.2[(g)] |

[(a)]Data from EUPHOROS Project (Montero et al. 2011); [(b)]Data from AGREE Project (Gołaszewski and de Viser 2012); [(c)]Bojacá et al. (2009); [(d)]Rezender et al. (1997); [(e)]MAAM (2012) ; [(f)]INE (2005) ; [(g)]FAO (2013b) ; [(h)]BLE (2013).

### *(c) Environmental indicators*

Environmental indicators to assess the potential implementation of RTGs in an entire retail park were based on the potential environmental benefits per kg of product. Environmental impact factors (i.e., environmental saving per kg) were calculated by comparing the potential RTG supply-chain (local) to the conventional supply-chain of tomatoes under greenhouse and with substrate. The comparison was under a life cycle perspective, namely from the horticultural production to the retail stage, thus showing the savings regarding the logistics. The geographic context of each study area defined the cultivation techniques used and tomato market trends to determine the conventional supply-chain. In this sense, specific environmental impact factors were calculated for each study area. Life cycle data for the calculations were based on Montero et al. (2011) and Sanyé-Mengual et al. (2013) (Input data and calculation processes are described in Appendix 1.4).

The assessed environmental indicators were the avoided energy consumption (MJ) due to logistic savings and the related avoided $CO_2$ emissions (kg of $CO_2$) per kg of tomato produced. Besides, Scenario B considered the effects of integrating the waste heat from the building to the greenhouse to optimize the crop production. In warm climates, crop yield is increased, while in cold climates waste heat substitutes the energy required to heat the greenhouse.

A new environmental indicator was added to evaluate the potential change of RWH (%).This is quantified by comparing the current RWH potential (in terms of $m^3$ of water harvested) and the short-term RWH potential (which refers to the RWH potential once the RTGs are implemented) (Equation 5.3). This indicator relies on the fact that leaning roofs (e.g. provided by the RTGs) have a higher run-off coefficient for RWH (RC = 0.9) than flat ones (RC = 0.62) (Farreny et al. 2011b). RWH potential was calculated as the addition of the individual RWH based on material, area, roof type and rainfall of each building in the retail parks.

$$(5.3)\ RWH\ improvement\ (\%) = \frac{short\text{−}term\ potential\ RWH\ (m^3)}{current\ potential\ RWH\ (m^3)}$$

## 5.3. Results and discussion

In the following section the results are presented as follows. First, potential implementation of RTGs in the case studies is accounted for and compared to previous studies on industrial and logistic areas. Second, the environmental impact factors calculated per kg of product for each study area are shown. Third, the potential benefits (production, environmental, self-supply) of isolated RTGs are discussed, which are later compared to the potentialities of an integrated RTG (scenario B) based on an industrial ecology approach. Indicators also show the improvement of RWH potential to observe the collateral benefits of RTGs (rooftop shape modification). Then, geographic preferences are identified based on different factors. Finally, the variables that most affect the outcomes are detected to highlight dependence relations.

### *5.3.1. Results of implementing of RTGs on retail parks*

#### Potential of implementing RTGs

The potential of implementing RTGs on retail parks is relevant and could be implemented in the short-term in 53.2 – 98.0% of most of the retail parks rooftops assessed (Table 5.5). However, the short-term potential for Colombian retail park is only 10.9%, since fewer buildings were suitable because of architectural constraints. Due to the low potential of Colombia, the guide was not further applied.

When compared with previous studies on industrial and logistics parks, retail parks show greater implementation potential for the same study area (Barcelona). While RTGs could be implemented in the short-term in 53.2 – 73.2% of the rooftops of the retail parks assessed, the short-term potential for the industrial park Zona Franca (Barcelona, Spain) was only of 8% (Sanyé-Mengual et al. 2015a). These results are related to the fact that buildings in retail parks tend to be more resistant than in industrial parks, and retail parks easily accomplish RTG requirements. Consequently, planning strategies for implementing RTGs in urban areas might focus on retail parks as a priority due to the higher potential regarding RTG implementation. Industrial areas showed a low potential due to architectural constraints, while residential rooftop usually are smaller and, thus open-field rooftop farming (i.e., without greenhouse technology) can be easily implemented.

#### Environmental impact factors by study area: Geographic variability

Prior to accounting the indicators of production, self-supply and environmental benefits (Step 3 of the guide), specific environmental impact factors per each study area were calculated as described in section 2.2.2c. Table 5.5 compiles the environmental impact factors per kg of tomato calculated for both scenario A and B. The maximum effect of the heat exchange in Scenario B is considered, although the efficiency is assessed below as a sensitivity parameter to discuss the potential benefits of i-RTGs.

***Table 5.5.*** *Environmental impact factors for indicators calculation (Step 3), by case study and country*

| | **ES** | | **PT** | **NL** | | **DE** | **CL** | **BR** |
|---|---|---|---|---|---|---|---|---|
| | **BCN-Sant Boi** | **BCN-Montigalà** | **Lisbon** | **Utrecht** | **Rotterdam** | **Berlin** | **Manizales** | **São Carlos** |
| **Scenario A (isolated)** | | | | | | | | |
| $CO_2$ savings (g of $CO_2$ per kg) | 433.5 | 433.5 | 349.4 | 455.9 | 477.5 | 864.2 | 694.8 | 559.0 |
| Energy savings (MJ per kg) | 12.1 | 12.1 | 9.5 | 10.6 | 11.0 | 18.24 | 14.0 | 11.7 |
| **Scenario B (i-RTG)(100%)** | | | | | | | | |
| $CO_2$ savings (g of $CO_2$ per kg) | 599.1 | 599.1 | 476.7 | 1,042.0 | 979.7 | 1,300 | 873.1 | 767.0 |
| Energy savings (MJ per kg) | 14.7 | 14.7 | 11.6 | 16.7 | 15.7 | 25.9 | 16.6 | 14.8 |

Environmental impact factors strongly vary among the different case studies (Table 5.5) due to climatic conditions and market trends. First, climatic conditions define the impact related to the production stage because of the different resources requisites (i.e., energy consumption, water use, and infrastructure). In warm climates (e.g., Spain), tomato production is performed in unheated multitunnel greenhouse with a low energy consumption ($\approx 0\ MJ \cdot kg^{-1}$) and a high water consumption due to higher evapotranspiration, but crop yield is lower. In cold climates (e.g., The Netherlands), heated VENLO greenhouses are used for horticultural production with large yields and low water demand but with large energy demand ($23.36\ MJ \cdot kg^{-1}$) (Appendix 1.3). Second, in warm areas the conventional production is usually performed in the same country and the distribution distance is short, particularly for Brazil and Portugal (70 km). However, in cold areas transportation distance is larger (for Germany is of 1300 km), apart from the case of The Netherlands, which most of the national demand is supplied locally and transportation requirements are shorter (30 – 100 km) (Appendix 1.3). As a consequence of the several factors, the supply-chain avoided impact values are higher for cold areas (600 g of $CO_2$ and 13 MJ per kg of tomato, on average) than for warm ones (494 g of $CO_2$ and 11.9 MJ per kg of tomato, on average) (Table 5.5).

Furthermore, the expected consequences of the energy exchange in i-RTGs (Scenario B) diverge among locations due to a different potential use of the residual heat from the building. In cold areas this input is used to substitute the energy consumption for maintaining the controlled atmosphere temperatures (i.e., $23.36\ MJ \cdot kg^{-1}$), while in warm areas this is used to increase the crop yield without using extra energy. Figure 5.2 shows the variability of introducing the residual heat from the building into the greenhouse, according to its efficiency on increasing the crop yield (warm areas) or substituting the current energy consumption for heating the greenhouse (cold areas). The potential increase in environmental savings between Scenario A and B is larger for the cold areas (up to 1.8 times higher avoided $CO_2$ emissions per tomato) than for the warm ones (up to 1.3 times higher) (Table 5.5).

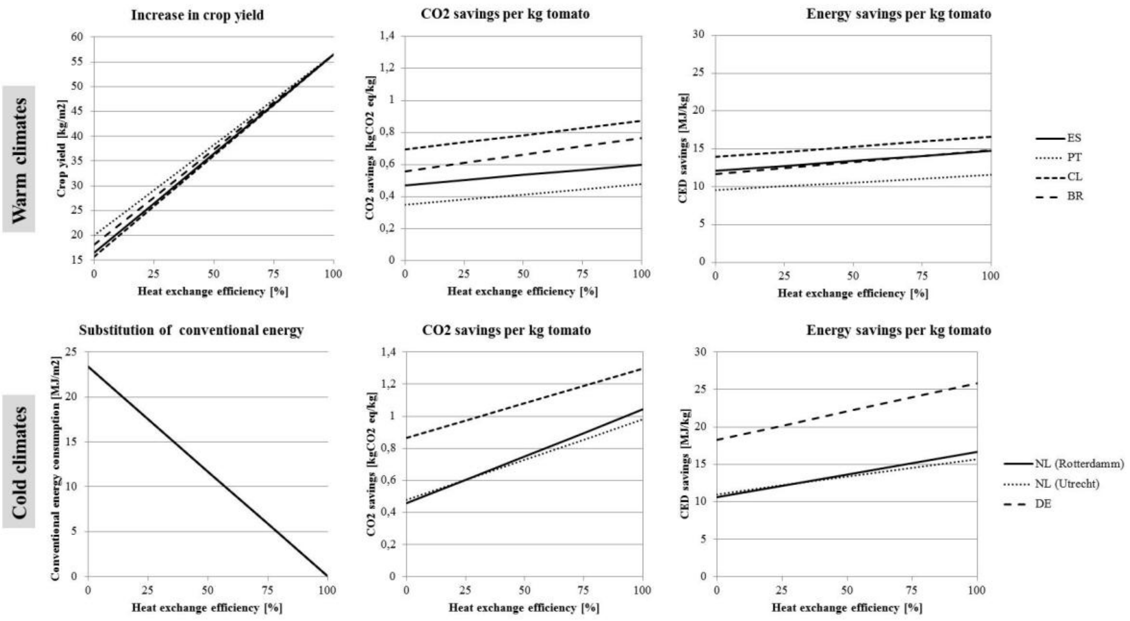


***Figure 5.2.*** *Cultivation parameters for scenario B, $CO_2$ savings and energy savings per kg of tomato, by case study and heat energy efficiency (%).*

### Potential production, environmental benefits and contribution to urban self-supply of isolated RTGs in retail parks (Scenario A)

This section evaluates the performance of RTGs without synergy with the building (i.e., no residual heat exchange). Per area of retail park, tomato production could be from 30.9 to 234 tonnes of tomato and the $CO_2$ savings would range from 15.8 to 135.8 tonnes of $CO_2$ eq. per ha and year. At the retail park level, the potential tomato production could be from 250 to 6,800 tons of tomato, which are associated to the environmental savings of local production: between 143.7 and 5,880.2 tonnes of $CO_2$ eq. and 3,000 and 124,000 GJ, depending on the case study (Table 5.6). Regarding the contribution to local food production and urban self-supply, RTG production could satisfy the average yearly intake of tomato of from 25,000 (Brazil) to 370,000 (Rotterdam) people per park and year. The implementation of isolated RTGs could supply between the 3.8 and the 59.3% of the tomato demand of the population of the city where the retail parks are placed, being higher in cold areas due to a more efficient crop technology (i.e., higher crop yields) (Table 5.6).

***Table 5.6.*** *RTG potential, results for Scenario A (isolated RTG), by case study and country (Indicators were not assessed for Colombia due to the low short-term RTG potential obtained)*

| | **Spain** | | **Portugal** | **The Netherlands** | | **Germany** | **Brazil** | **Colombia** |
|---|---|---|---|---|---|---|---|---|
| | **Sant Boi** | **Montigalà** | **Alfragide** | **Utrecht** | **Rotterdam** | **Berlin** | **São Carlos** | **Manizales** |
| **Extension** | | | | | | | | |
| Park area (ha) | 25.2 | 20.27 | 35.10 | 13.30 | 17.01 | 43.25 | 8.30 | 1.58 |
| Rooftop area (ha) | 7.58 | 9.80 | 10.22 | 7.04 | 8.53 | 12.29 | 2.50 | 0.60 |
| **RTG potential** | | | | | | | | |
| Short-term (%) | 73.7 | 53.2 | 82.4 | 62.5 | 84.4 | 98.0 | 57.0 | 10.9 |
| Short-term (ha) | 5.58 | 5.22 | 8.42 | 2.65 | 7.06 | 12.04 | 0.07 | 1.42 |
| **Indicators** | | | | | | | | |
| **Crop yield (kg·m$^{-2}$)** | **16.5** | **16.5** | **20.0** | **56.5** | **56.5** | **56.5** | **18.1** | **15.7** |
| Production (t tomatoes·year$^{-1}$) | 921.2 | 860.8 | 1,684.0 | 1,497.7 | 4,067.6 | 6,804.2 | 257.0 | - |
| GEH emissions savings (t $CO_2$·year$^{-1}$) | 399.4 | 373.2 | 588.4 | 682.9 | 1,942.3 | 5,880.2 | 143.7 | - |
| Energy consumed savings (GJ·year$^{-1}$) | 11,128.6 | 10,398.6 | 16,071.7 | 15,938.5 | 44,712.5 | 124,108.9 | 3,000.6 | - |
| Self-supply potential (people·year$^{-1}$) | 53,561 | 50,047 | 120,282 | 137,406 | 373,176 | 330,302 | 25,198 | - |
| Self-supply degree (%) | 3.8 | 3.5 | 12.2 | 43.4 | 59.3 | 3.7 | 11.5 | - |

## Potential benefits of i-RTGs (Scenario B)

Table 5.7 shows the potential outputs of implementing i-RTGs in the analysed retail parks, when considering the maximum effect of the residual heat integration. This means that crop yield is boost up to 56.5kg·m$^{-2}$ in warm climates and the residual heat from the building substitutes the overall conventional energy consumption for heating purposes in cold climates. Colombia is excluded of the assessment as in previous sections.

***Table 5.7.*** *Results for Scenario B (integrated RTG), considering a 100% efficiency, by case study and country*

| | **Spain** | | **Portugal** | **The Netherlands** | | **Germany** | **Brazil** |
|---|---|---|---|---|---|---|---|
| | **Sant Boi** | **Montigalà** | **Alfragide** | **Utrecht** | **Rotterdam** | **Berlin** | **São Carlos** |
| **Scenario B (i-RTGs) (kg/m2)** | 56.5 | 56.5 | 56.5 | 56.5 | 56.5 | 56.5 | 56.5 |
| Production (t tomatoes·year$^{-1}$) | 3,154.6 | 2,947.6 | 4,757.2 | 1,497.7 | 4,067.6 | 6,804.2 | 802.3 |
| GEH emissions savings (t $CO_2$·year$^{-1}$) | 1,889.9 | 1,765.9 | 2,267.7 | 1,560.6 | 3,985.0 | 8,845.5 | 615.4 |
| Energy consumed savings (GJ·year$^{-1}$) | 46,372.1 | 43,330.2 | 55,183.2 | 25,012.1 | 63,861.6 | 176,093.1 | 11,874.0 |
| Self-supply potential (people·year$^{-1}$) | 183,405 | 171,374 | 339,798 | 137,407 | 373,176 | 330,302 | 78,657 |
| Self-supply degree (%) | 12.9 | 12.1 | 34.5 | 43.4 | 59.3 | 10.4 | 36.0 |

The energy exchange between the greenhouse and the building affected positively all the case studies. When considering the maximum effect of integrating the residual heat from the building into the greenhouse, all the indicators are improved. Environmental savings are higher (2.1 times for avoided $CO_2$ emissions and 1.8 for energy consumption, on average). For warm climates, there is a rise in production and consequently in food self-supply (1.5 times larger, on average). On average, the interconnection between the greenhouse and the building may represent an increase in production from 117 (Scenario A) to 206 (Scenario B) tonnes of tomato per ha, a rise in the avoided environmental impact from 60 to 152 tonnes of $CO_2$ eq. per ha and from 1,415 to 3,100 avoided GJ per ha (Table 5.7).

In this context, the results highlight the substantial contribution of considering an industrial ecology approach when implementing RTGs in retail parks and, thus, promote the installation of integrated RTGs. This study shows the maximum benefits of i-RTGs (Table 5.7) although the potential production and environmental benefits depend on the heat exchange efficiency (i.e., from 0% to 100%) (Figure 5.2). Further RTG projects will shed light on the efficiency and, thus, on the real benefits of these systems. Besides, this paper only focuses on a mono-directional exchange of energy due to lack of data for further analysis and only consider the exchange of energy although water and $CO_2$ flows can also be integrated. Nevertheless, theoretical works about i-RTGs proposes a synergic relation between the greenhouse and the building (Cerón-Palma ,2012). Thereby, further environmental benefits may be obtained by implementing i-RTGs, becoming an innovative way of improving both the horticulture and the building sectors from a synergic approach.

### Improving Rainwater Harvesting (RWH) as a collateral effect

The improvement in RWH potential ranged between 14 and 45% among the different case studies (Table 5.8) because of the larger catchment coefficient of inclined roofs (i.e., greenhouse roofs) than flat ones. Moreover, the total amount of harvested rainwater could plenty satisfy the crop water requirements of RTGs activity in the assessed retail parks (>100%), apart from Berlin due to a lower rainfall (69%). Thus, rainwater could be also used in other spaces of the building (e.g., garden irrigation), depending of the water quality. Accordingly, the implementation of RTGs in retail parks could have indirect positive effects not only on the overall system (increase in RWH) but also on the horticultural production itself (crop water self-sufficiency).

***Table 5.8.*** *Results for Rainwater Harvesting (RWH) improvement, by case study and country*

| | **Spain** | | **Portugal** | **The Netherlands** | | **Germany** | **Brazil** |
|---|---|---|---|---|---|---|---|
| | **Sant Boi** | **Montigalà** | **Alfragide** | **Utrecht** | **Rotterdam** | **Berlin** | **São Carlos** |
| Current RWH potential ($m^3$) | 30,115.5 | 43,232.8 | 51,325.0 | 49,821.5 | 45,595.4 | 45,291.3 | 25,446.3 |
| Short-term RWH potential ($m^3$) | 39,947.8 | 52,420.2 | 69,663.3 | 56,978.9 | 62,580.9 | 65,852.0 | 31,256.8 |
| Improvement (%) | 32.6 | 21.3 | 35.7 | 14.4 | 37.3 | 45.4 | 22.8 |
| Crop water self-sufficiency (%) | 150.6 | 211.5 | 173.8 | 270.6 | 111.6 | 68.8 | 460.7 |

## *5.3.2. Geographic variability and RTG implementation*

The results of the different study areas revealed that some factors are geographic-dependant, and the study areas can be ranked based on the preference of implementing RTGs. This can be assessed in different decision-making scenarios where production, energy savings, environmental savings or RWH potential is the driver. In Table 5.9, the different study areas are identified as the optimal location for implementing RTGs according to different criteria.

***Table 5.9.*** *Most preferable geographic selection for RTG implementation according to different criteria, results for Scenario A (isolated RTGs) and Scenario B (i-RTG), by country.*

| **RTG implementation** | **Europe** | | | | **South America** | |
|---|---|---|---|---|---|---|
| | **ES** | **PT** | **NL** | **DE** | **CL*** | **BR** |
| *Isolated RTGs:* | | | | | | |
| - Production | | | ● | ● | | ● |
| - Energy savings | ● | | | ● | ● | |
| - Environmental savings | ● | | | ● | ● | ● |
| - RWH potential | | | | | | ● |
| *Interconnected RTGs:* | | | | | | |
| - Production | ● | ● | | | ● | ● |
| - Energy savings | | | ● | ● | | |
| - Environmental savings | | | ● | ● | | |
| - RWH potential | | | | | | ● |

**Indications for Colombia respond to the calculated environmental savings and the potential crop yield increase in Scenario B.*

For isolated RTGs, cold areas seem the best place in Europe to implement RTGs due to higher crop yields in heated horticulture technologies. In South America, Brazil shows higher tomato productivity. However, in environmental terms, Germany, Spain and Colombia would be the most preferable options due to the larger savings. For i-RTGs, the potential production will benefit all the warm areas, as it is highly increased. However, energy and environmental benefits will now situate cold areas as the best options due to the hypothetical avoided energy input in the horticultural production. Regarding RWH improvement and crop water self-sufficiency, Brazil shows the largest potential.

### *5.3.3. Influential parameters on potential RTG implementation and benefits*

Results showed dependence on certain parameters and variables correlation (Pearson's coefficient) was calculated (Correlation values are detailed in Appendix 1.5). First, the short-term potential of implementing RTGs mainly relies on the architecture (e.g., type of roof) and design of the retail park (e.g., park size). Second, the potential benefits related to RTGs can be a consequence of the short-term potential, production parameters or other factors.

#### Influence of architecture and design of retail parks

Architecture has an important role in the selection of rooftops as suitable for implementing RTGs because technical requirements are the most limiting ones. According to the results obtained, the most limiting factor related to the short-term potential was the shape of the rooftop (i.e., flat to be suitable), with a strong correlation (r=0.81). However, this trend contrasts the results for industrial and logistic parks, for the latter material is the limiting factor, in contrast to the type of materials used in retail park that tend to be more homogeneous. As an exception, the case study of Colombia behaves as an industrial park and the material was the limiting factor (89% of the rooftops were made of metal sheet, categorized as non-resistant for RTG purposes) although 100% of the rooftops were flat. Architecture was thus responsible for obtaining the lowest short-term potential (11%) in Manizales. The design of the park also influenced the results. First, the RTG potential presented a positive relationship with the size of the retail park, i.e., the larger the retail park, the higher the short-term potential (r=0.60). Second, the type of retail park, compact or diffuse (Table 5.2), was also important since the short-term potential is slightly higher in compact retail parks with greater rooftop ratios (10% higher, on average).

Thereby, when designing new retail parks these issues may be contemplated if local production is considered by planners. On the architecture area, retail parks may tend to be homogeneous, flat and resistant (concrete) buildings, which could result in a large RTG potential. On the other hand, RTG planners may prioritize projects in large and compact retail parks, where the implementation of RTGs may easily success due to a higher RTG potential.

### Production, environmental savings and self-supply

The potential production showed strong dependence on the design of the park but also on production parameters: correlation to rooftop ratio (which defines when a retail park is compact or dense) was r=0.58 and moderate correlation to crop productivity was r=0.37. Hence, i-RTGs can strengthen the potential contribution of RTGs to local production by taking advantage from the residual heat from the building thereby boosting crop yield. Environmental savings values vary according to the production per area of each park (r=0.42), but mostly depends on the short-term potential (r=0.70) and the avoided impact value per kg of tomato (r=0.56). Therefore, the potential environmental benefits rely most on the design of the retail park and on the national produce market, which determines the avoided distribution stage. Third, self-supply results depend more on the supply than on the demand side, as the factor that influenced the most was the production per area (r=0.88), rather than the average intake or the design of the park (r<0.4). Finally, the increase in RWH potential is determined by the presence of flat roofs (r=0.97) and the short-term potential of the retail park (r=0.85). However, no relation was found with the rainfall pattern of the study area (r<0.1).

## 5.4. Conclusions

Retail parks showed a notable short-term potential for implementing RTGs: between 53.2 and 98% of the buildings of the case studies, apart from Manizales with a potential only of 10.9% due to design constrains. Also, RTGs had a large potential in terms of production values, environmental savings and contribution to urban food self-supply. These results were higher than for industrial and logistics parks, pointing out that urban RTG projects may be placed in retail parks, preferably, since the architecture of retail parks tend to easily accomplish RTG requirements. Moreover, the RTG production could be directly sold in the supermarkets avoiding the energy requirements of distributing the produce, as well as the implementation of RTGs in retail parks could also result in an effective communication tool due to the large number of customers.

Notwithstanding these results, the consideration of an industrial ecology approach in the design of RTGs could boost both the food production and the resulting benefits. Integrated RTGs (i-RTGs) could be a demonstrative system of a symbiotic metabolism of integrated functions. An integration of the residual heat from the building into the greenhouse might increase crop yields in warm climates and reduce the environmental impact of heated greenhouses in cold climates. However, no experimental data is available to determine the efficiency of the metabolic exchange and further research is needed to show the overall environmental balance of these systems. The potential of water and gaseous exchanges, a synergic metabolism (i.e., double exchange) and their effect to other crops (e.g., lettuce) may be assessed in experimental projects to obtain more accurate results that could be extrapolated to planning projects.

As a collateral positive effect, RTGs modify the shape of the rooftop of a building, which changes from flat (building) to sloped (greenhouse). This effect could signify an increase between the 14 and 45% of the overall rainwater harvesting. The resulting RWH potential could satisfy the crop water demand, apart from in Germany where rainfall is lower (69% crop water self-sufficiency).

The implementation of RTGs can be of interest for different motivations, for example the potential production. However, the geographic variability results on divergent outputs for the various indicators. Consequently, depending on the decision-making criterion the preferable study area would be different. When considering food production as the driver of an RTG project, higher crop yields would determine the better place. For isolated RTGs, countries where heated greenhouses are implemented would be of great interest. However, the implementation of i-RTGs would benefit warm climates where the crop yield is increased by means of residual heat.

Finally, the RTG short-term potential depends on the architecture and design of the park. Higher potential is found in larger parks and depends on the presence of flat roofs and the resistance of the structures. Therefore, recommendation for planners should be to prioritize RTG projects on this kind of retail parks and to consider these requirements in the development of new ones.

# Part III

## Assessment of rooftop greenhouses

# Chapter 6

## An environmental and economic life cycle assessment of rooftop greenhouse (RTG) implementation in Barcelona, Spain.

*Assessing new forms of urban agriculture from the greenhouse structure to the final product level*

Picture: *Tomato production in the RTG-Lab (Bellaterra, Spain) (©Esther Sanyé-Mengual)*

# Chapter 6

This chapter is based on the journal paper:

Sanyé-Mengual E, Oliver-Solà J, Montero JI, Rieradevall J (2015) An environmental and economic life cycle assessment of Rooftop Greenhouse (RTG) implementation in Barcelona, Spain. Assessing new forms of urban agriculture from the greenhouse structure to the final product level. *International Journal of Life Cycle Assessment* 20(3):350-366 (DOI: 10.1007/s11367-014-0836-9)

## Abstract

Rooftop greenhouses (RTGs) are increasing as a new form of urban agriculture. Several environmental, economic, and social benefits have been attributed to the implementation of RTGs. However, the environmental burdens and economic costs of adapting greenhouse structures to the current building legislation were pointed out as a limitation of these systems in the literature. In this sense, this paper aims to analyse the environmental and economic performance of RTGs in Barcelona.

A real RTG project is here analysed and compared to an industrial greenhouse system (i.e. multi-tunnel), from a life cycle perspective. Life cycle assessment (LCA) and life cycle costing (LCC) methods are followed in the assessment. The analysis is divided into three parts that progressively expand the system boundaries: greenhouse structure (cradle-to-grave), at the production point (cradle-to-farm gate), and at the consumption point (cradle-to-consumer). The applied LCIA methods are the ReCiPe (hierarchical, midpoint) and the cumulative energy demand. A cost-benefit analysis (CBA) approach is considered in the LCC. For the horticultural activity, a crop yield of 25 $kg \cdot m^{-2}$ is assumed for the RTG reference scenario. However, sensitivity analyses regarding the crop yield are performed during the whole assessment.

The greenhouse structure of an RTG has an environmental impact between 17 and 75% higher and an economic cost 2.8 times higher than a multi-tunnel greenhouse. For the reference scenario (yield 25 $kg \cdot m^{-2}$), 1 kg of tomato produced in an RTG at the production point has a lower environmental impact (10–19%) but a higher economic cost (24%) than in a multi-tunnel system. At the consumption point, environmental savings are up to 42% for local RTGs tomatoes, which are also 21% cheaper than conventional tomatoes from multi-tunnel greenhouses in Almeria. However, the sensitivity assessment shows that the crop efficiency is determinant. Low yields can produce impacting and expensive vegetables, although integrated RTGs, which can take advantage from the residual energy from the building, can lead to low impacting and cheap local food products.

RTGs face law limitations that make the greenhouse structure less environmentally friendly and less economically competitive than current industrial greenhouses. However, as horticultural systems and local production systems, RTGs can become an environmentally friendly option to further develop urban agriculture. Besides, attention is paid to the crop yield and, thus, further developments on integrated RTGs and their potential increase in crop yields (i.e. exchange of heat and $CO_2$ with the building) are of great interest.

Keywords: Building-integrated agriculture, Industrial ecology, Local production, Rooftop farming, Urban agriculture.

## 6.1. Introduction

The construction of rooftop greenhouses (RTGs) on urban buildings has intensified in recent years. The trend has resulted from a growing interest in the development of new agricultural spaces and in the promotion of food self-sufficiency in urban areas. An RTG consists of a greenhouse built on the roof of a building that typically generates produce via soilless culture systems (Cerón-Palma et al. 2012). These structures are considered a component of the “building-based urban agriculture (UA)” movement, which is also referred to as vertical farming (VF) (Despommier 2008; Despommier 2009; Despommier 2010; Despommier 2011), Skyfarming (Germer et al. 2011), and zero-acreage farming (ZFarming) . In recent years, VF has grown in popularity leading to the creation of a sector that seeks improving indoor cropping technologies and designing VF buildings. All devoted to boost local production, indoor farms in Singapore use high-yield hydroponic technology (Sky Greens), spherical buildings are designed by Plantagon (Sweden) or former warehouses are filled with LED-lighted hydroponic systems in the USA (such as Green Spirit Farms).

Table 1 provides a list of RTG projects and companies currently in operation, which are largely located in North America. Gotham Greens, The Vinegar Factory, and Lufa Farms are local producers based in New York and Montreal that have built RTGs ranging in size from 830 to 2,900 m$^2$. Produce from these farms is sold in supermarkets or their own specialized shops or distributed through a community-supported agriculture (CSA) model (Resh 2012). Vegetables grown from RTGs have been widely accepted by customers in such a way that Lufa Farms is currently planning to build two additional RTGs, thereby increasing the company’s overall production area to 18,000 m$^2$. Other companies are planning to build RTGs in several Canadian cities, and the Blue Sea Development Corporation aims to construct an RTG on top of an apartment building in New York City. In Europe, RTGs are currently being operated for research purposes and therefore remain as experimental projects. Beyond food production, Vida Verde, a Dutch floriculture company based in Honselersdijk, built an RTG on top of its logistics centre for temporary product storage due to high land prices (400€·m$^{-2}$) (pers. comm. Vida Verde).

Though RTG projects currently exist as isolated plots, RTGs can also be integrated with a building and thereby provide further benefits. Integrated RTGs (i-RTGs) can exchange metabolic flows with the building upon which they are built based on the industrial ecology concept (Cerón-Palma et al. 2012). In particular, i-RTGs can exchange and optimise the following flows: energy, water and air emissions (e.g. $CO_2$). For instance, the ICTA-ICP research-oriented i-RTG was designed to exchange energy and $CO_2$ flows with the building and will also utilise rooftop rainwater (see Section 6.2).

***Table 6.1.*** *Characteristics of current RTG experiences and projects.*

| **Name** | **City** | **Area** | **Year** | **Produce** | **Building type** | **Type** |
|---|---|---|---|---|---|---|
| Gotham Greens[a] | Brooklyn, NY, United States | 1,400 $m^2$ | 2011 | 6 varieties of lettuce and basil | Former warehouse | Isolated |
| The Vinegar Factory[b] | Manhattan, NY, United States | 830 $m^2$ | n.d. | Tomatoes, salad greens and herbs | Commercial | Isolated |
| Lufa Farms[c] | Montreal, Canada | 2,900 $m^2$ | 2011 | Greens, tomato, cucumber, pepper and eggplants | Commercial | Isolated |
| Forest houses | South Bronx, NY, United States | 930 $m^2$ | Project | - | Apartment building | Isolated |
| Local Garden[d] | Vancouver, Canada | 550 $m^2$ | Project | - | - | Isolated |
| Urban produce[e] | Toronto, Canada | 4,200 $m^2$ | Project | - | - | Isolated |
| VidaVerde | Honselersdijk, The Netherlands | n.d. | 2012 | Plant nursery Storage | Garden centre | Isolated |
| Fresh from the Roof | Berlin, Germany | 7,000 $m^2$ | Project | - | Former factory | Isolated |
| ICTA-ICP | Bellaterra, Spain | 250 $m^2$ | 2014 | Lettuce, tomato | Research centre | Integrated (i-RTG) |

*([a]http://www.gothamgreens.com, [b]http://www.elizabar.com, [c]https://lufa.com/, [d]http://www.localgarden.com/, [e]http://www.urbanproduce.ca/)*

### *6.1.1. RTG benefits*

RTGs (both isolated and integrated) can provide environmental, economic and social benefits and can therefore improve the sustainability of urban areas (Cerón-Palma et al. 2012; Specht et al. 2014). Such benefits can be found at different scales: by reducing transportation (product scale) (Sanyé-Mengual et al. 2013), lessening pressure on fertile agricultural areas (global scale) (Droege 2012) and increasing the availability of urban fresh produce (local scale) (Cerón-Palma et al. 2012). RTGs also benefit buildings differently depending on the type of RTG concerned. Isolated RTGs can provide thermal insulation for buildings and therefore reduce energy consumption for acclimatisation purposes (Cerón-Palma 2012). However, benefits associated with integrated RTGs are more significant. Integrated RTGs can optimise water metabolism processes and can utilise building-residual heat for agriculture production. Table 2 elaborates further on the numerous potential benefits of RTGs.

Environmental research has primarily focused on quantifying the abovementioned environmental benefits. At the food product level, Sanyé-Mengual et al. (2013) quantified environmental savings from local RTG production in Barcelona and found that resulting reductions in environmental impact from RTG production are related to reduced transportation. A comparison between the conventional supply chain and RTG local supply chain showed that RTG tomatoes grown in Barcelona could replace tomato production in Almeria (900 km) (the main tomato producer in Spain), thereby avoiding 441 g of $CO_2$ eq. and 12 MJ of energy consumed per kilogram. At the building-greenhouse system level, Cerón-Palma (2012) performed a preliminary assessment of i-RTGs. Energy modelling results illustrated the environmental benefits of energy flow exchange between RTGs and office buildings. The results showed that the introduction of residual heat from the greenhouse into the building on an ideal winter day could substitute 87 kWh of the heating demand.

The literature has thus not yet extensively focused on the potential environmental impacts of RTGs or their economic feasibility. The RTG structure has been found to be a possible barrier to the implementation of such systems due to environmental burdens associated with materials and investments required (Cerón-Palma et al. 2012). In particular, meeting legal requirements for buildings in urban areas involves reinforcing the RTG structure, which results in increased resource consumption. Furthermore, the construction stage is more energy intensive due to more intensive machinery use (e.g. rising materials to the rooftop). Finally, although real experiences already exist, there is a lack of research about real projects that could considerably contribute to a comprehensive evaluation of the potential benefits of RTGs.

***Table 6.2.*** *Main potential environmental (E), economic (Ec) and social (S) benefits of Rooftop Greenhouses (RTGs), by scale (global, local, building-greenhouse system and product). Benefits are divided into two categories: general benefits of local food production (●) and specific benefits of RTGs (♦).*

| Scale | Potential benefit | E | Ec | S |
|---|---|---|---|---|
| **Global** | Enhancing closed cycles in urban food flows[a] | ● | ● | ● |
| | Contributing to food self-supply[b,c] and urban resilience to climate change[d] | ● | | ● |
| | Lessening pressure to fertile agricultural land[e] | ● | | |
| **Local** | Optimizing urban space[a,f], revaluating unproductive spaces[a] and increasing urban multifunctionality[g] | ♦ | ♦ | ♦ |
| | Naturalising urban areas[a] and increasing urban biodiversity | ♦ | ♦ | ♦ |
| | Increasing availability of fresh produce[a] and reducing product losses[h] | ● | | ● |
| | New technology and market development | | ♦ | ♦ |
| **System (isolated RTGs)** | Reducing building energy consumption due to thermal insulation[i] | ♦ | ♦ | |
| **System (i-RTGs)** | Recycling of building wastewater[a] and water use optimization through recirculation[j] | ♦ | ♦ | |
| | Reducing building energy consumption due to insulation and heat exchange[i] | ♦ | ♦ | |
| | Using building-residual energy and $CO_2$ in greenhouse production[a] | ♦ | ♦ | |
| **Product** | Avoiding distribution stage[a,g,k] | ● | ● | |
| | Production with low resources and energy inputs[a] | ♦ | ♦ | |
| | Increasing food quality[e] | ♦ | ♦ | ♦ |
| | Producer-consumer direct and short-term relation[l] | | ● | ● |

*([a]Cerón-Palma et al. (2012); [b]Barthel and Isendahl (2013); [c]Kirwan and Maye (2012); [d]Despommier (2010); [e]Droege (2012); [f]Torreggiani et al. (2012); [g]Arosemena (2012); [h]Sanyé-Mengual et al. (2013); [i]Cerón-Palma et al. (2011); [ji]Montero et al. (2009); [k]Jones (2002); [l]Wallgren and Höjer (2009)).*

### *6.1.2. Objectives*

Given this context, the goal of this paper is to complete an environmental and economic assessment of RTGs with a focus on the RTG as a greenhouse structure and horticultural production system. This new urban horticultural structure is also compared against the multi-tunnel greenhouse model as a representative conventional greenhouse commonly used in Spain. To accomplish these objectives, this paper explores the following research questions:

a) As greenhouse structures, what are the main differences between RTGs and multi-tunnel greenhouses in environmental and economic terms?

b) At the production point (i.e. from a cradle-to-farm gate perspective), what are the main differences between RTGs and multi-tunnel greenhouses in environmental and economic terms?

c) At the consumption point (i.e. from a cradle-to-consumer perspective), what are the main differences between the local RTG supply chain and conventional multi-tunnel production in environmental and economic terms?

d) How sensitive are the results to crop yield variability given that i-RTGs may increase crop yields by exchanging energy and $CO_2$ with buildings?

## 6.2. The ICTA-ICP building rooftop greenhouse

In 2014, the research-oriented i-RTG was constructed on the top of the building that hosts the Institute of Environmental Science and Technology (ICTA) and Catalan Institute of Palaeontology (ICP). The building has an area of 7,500 $m^2$ (six floors) and is situated in the Universitat Autònoma of Barcelona (UAB) campus (Bellaterra, Barcelona). The building design is based on compact volume, reversibility and multifunctionality, energy efficiency, passive house, greenhouse and building-integrated agriculture principles.

The rooftop greenhouse lab (RTG-Lab), which consists of two 125 $m^2$ RTGs (Fig. 1), is placed on the building roof (Fig. 1). The purpose of the RTG-Lab is to demonstrate the feasibility of RTGs in Mediterranean areas and the potentialities of i-RTGs. The i-RTG will utilise residual heat from the building (e.g. lab air), $CO_2$ concentrations in this residual air (i.e. which will be used as natural fertiliser) and rainwater collected from the rooftop. More specifically, residual heat and $CO_2$ integration are expected to increase crop yields.

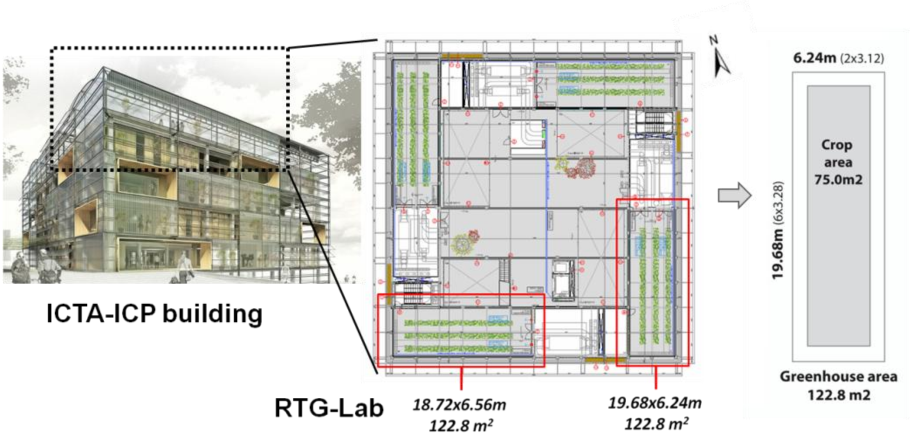


***Figure 6.1.*** *Layout of the RTG-Lab, situation in the ICTA-ICP building, and rooftop greenhouse dimensions (The RTG elements are detailed in Supporting Information 1).*

Notwithstanding the potential benefits of i-RTGs, the present paper analyses the greenhouse structure and predicts potential crop outputs but does not include an assessment on flow exchange due to lacking data on this issue. A number of legal requirements were addressed throughout the construction of the RTG and ICTA-ICP building to comply with the Spanish Technical Code of Edification (CTE) (RD 314/2006 (BOE 2006)) and fire safety laws (RD 2267/2004 (BOE 2004), Law 3/2010 (BOE 2010)). These modifications resulted in an RTG structure that utilises larger amounts of materials, some of which may also have a higher environmental impact compared to conventional greenhouse components. First, the RTG structure was reinforced to conform to CTE requirements, and thus, additional resources were used. Second, LDPE was not permitted for use as the greenhouse roof due to its incompatibility with safety requirements (e.g. fire) and thus, the RTG cover was constructed from polycarbonate, resulting in a higher use of resources per area (i.e. thicker material) and the use of higher-impact materials.

## 6.3. Life Cycle Assessment (LCA and LCC)

A life cycle approach is employed for both the environmental and the economic analyses. The life cycle assessment (LCA) method (ISO 2006a) quantifies the environmental burdens of the analysed systems. The life cycle costing (LCC) (ISO 2008) method assesses their economic performance.

### *6.3.1. Goal and scope*

The RTG assessment is divided into three parts to evaluate this new urban horticulture system from its greenhouse structure to its final product level. Consequently, the analysis progressively expands system boundaries as illustrated in Fig. 2.

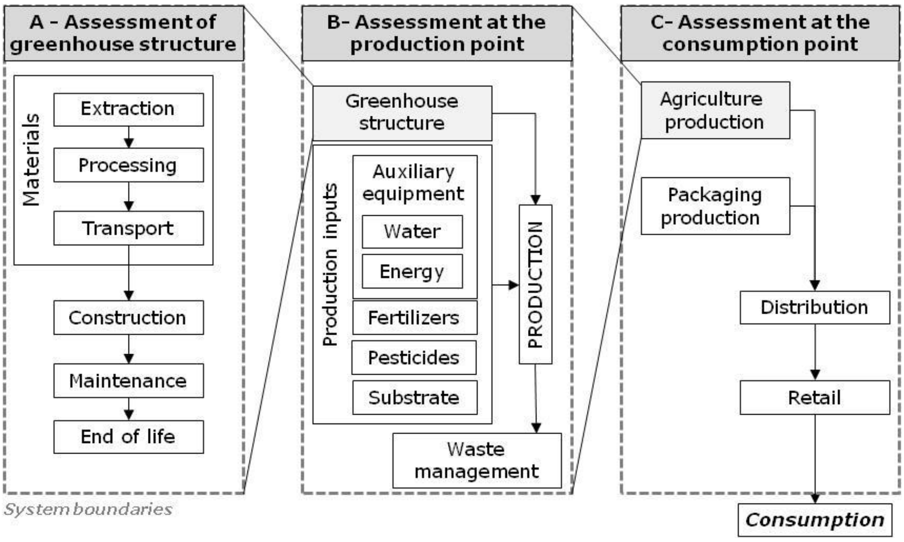


***Figure 6.2.*** *System boundaries and life cycle stages of the three assessments: greenhouse structure (cradle-to-grave), production point (cradle-to- farm gate), and consumption point (cradle-to-consumer).*

### (i) Greenhouse structure assessment:

The RTG-Lab greenhouse structure is analysed using a cradle-to-grave approach to quantify related environmental burdens and economic costs. The multi-tunnel greenhouse structure is referred to as a conventional horticulture system for comparative purposes. The multi-tunnel greenhouse is a steel-framed, arched roofed greenhouse with vertical sidewalls (Antón et al. 2005; Montero et al. 2011) that is commonly used in Mediterranean countries. The assessment includes the following stages: materials (extraction, processing and transportation), construction, maintenance and end of life (Fig. 2). The functional unit of the assessment is 1 $m^2$ of a greenhouse structure for a timeframe of 1 year. Although the functional unit corresponds to 1 year, the assessment considers the divergent lifespan of both greenhouse structures. The lifespan of the RTG is 50 years according to project data and building elements, whereas the lifespan of a multi-tunnel greenhouse is 15 years according to regulations (CEN 2001).

### (ii) Assessment at the production point:

The production in a RTG is analysed and compared to that in a multi-tunnel system using a cradle-to-farm gate perspective. The system boundaries of horticultural production include the greenhouse structure, the production inputs and the waste management (Fig. 2). Tomato production in a multi-tunnel greenhouse in Almeria is used as the conventional system. Tomato production from Almeria is selected due to its importance to the vegetable market of the study area. Tomatoes are the second most frequently sold product (14% of share) in MercaBarna (the food distribution centre of Barcelona), and 60% of this produce is produced in Almeria (MercaBarna 2014). While the RTG is situated in Barcelona, the multi-tunnel system is located in Almeria. As a result, the crop periods of the two systems differ due to climatic conditions.

While tomatoes are produced in Almeria as a 9-month crop (because the summer season is too hot for horticultural production), the crop period can extend to 11months in Barcelona by combining two crop cycles: the winter-summer and autumn-winter cycles. This extension is made possible through the introduction of residual heat from the building into the greenhouse, thereby extending the crop period during colder months. The functional unit of the assessment is 1 kg of tomatoes produced over 1 year at the farm gate.

### (iii) Assessment at the consumption point:

A cradle-to-consumer approach is used to compare the two systems at the consumption point. Accordingly, system boundaries are expanded to include additional life cycle stages: agricultural production, packaging production, distribution and retail. The consumption phase is excluded from the assessment due to its dependence on tomato preparation methods (e.g. from raw consumption to oven-grilled) (Fig. 2). With respect to distribution, the RTG represents a case of local production in which production is driven directly to the retail location with limited transport (25 km from Bellaterra to Barcelona). In contrast, the conventional case includes three different transportation stages (900 km from Almeria to Barcelona), and tomatoes are distributed through a food distribution centre. The functional unit of the assessment is 1 kg of tomatoes retailed for consumption in Barcelona.

## *6.3.2 Life cycle inventory*

### (i) Greenhouse structure assessment

RTG and conventional multi-tunnel greenhouse inventory data and costs are detailed in the Electronic Supplementary Material (Supporting Information 4). The following sections describe assumptions made with respect to the data compilation for both systems.

*RTG*

RTG inventory and economic cost data are drawn from ICTA-ICP building architectural project records, data provided by producers, and our own calculations. Stages related to materials (extraction and processing) are defined according to the structural design of the project. Transportation requirements for the materials are calculated based on the distance of the destination from the production site, as shown in the Electronic Supplementary Material (Supporting Information 2). The construction stage accounts for both the labour and energy consumption requirements of machinery used to raise the materials to the rooftop. Construction machinery consumes electricity from the grid, and total consumption levels are calculated according to technical specifications and construction requirements (detailed data is provided in the Electronic Supplementary Material (Supporting Information 2)). The construction stage does not consider the occupation of land, since RTGs take advantage from available surfaces in cities while land use and occupation corresponds to the existing building. Structure maintenance is calculated based on the lifespans of different materials according to data from producers (Electronic Supplementary Material, Supporting Information 1). For each material, the environmental burdens and economic costs of the maintenance are calculated as the quantity of material needed to achieve the expected RTG lifespan (50 years). Finally, because the structure is designed to be 100 % recyclable, only transportation is considered (recycling plants are located 30 km away from the site). This approach is appropriate because waste material recycling practices are excluded from the system boundaries due to the fact they are included in future life cycles as input processes (Ekvall and Tillman 1997).

Specific data on concrete manufacturing are obtained from the regional iTec database (ITeC 2012). Electricity mixes in 2013 for Spain (REE 2013), the UK (DECC 2014) and the Netherlands (CBS 2013a; CBS 2013b) are used in the materials processing assessment. The ecoinvent database v2.2 (Swiss Center for Life Cycle Inventories 2010) is used to collect background data on material LCI, processing and transportation characteristics. Costs are obtained from ICTA-ICP building architectural project records.

*Conventional system: multi-tunnel greenhouse*

Inventory and economic cost data for the conventional multi-tunnel greenhouse design are obtained from EUPHOROS project data (Montero et al. 2011). The data are adapted accordingly: recycled materials obtained from the market are modelled according to the cut-off perspective, where the input resource is assumed to be zero although processing steps are included (Ekvall and Tillman 1997), and the electricity mix in 2013 for Spain (REE 2013) is assumed for electricity consumption.

### (iii) Assessment at the production point: a cradle-to-farm gate perspective

Inventory data and costs of tomato production in an RTG and in a conventional multi-tunnel greenhouse are detailed in the Electronic Supplementary Material (Supporting Information 5). The following section lists assumptions made for both systems throughout the data compilation stage. RTG tomato production in Bellaterra (Spain) LCI and economic data are obtained from architectural project data and EUPHOROS project data (Montero et al. 2011) and from our own calculations. Apart from the greenhouse structure, production inputs include the following: auxiliary equipment, which includes equipment used in the crop system (i.e. substrate), for irrigation (i.e. pipes, pumps, injectors, water distribution systems, water tanks), for input application (i.e. fertiliser tank), and the consumption of water, energy, fertilisers and pesticides. Data on auxiliary equipment are drawn from EUPHOROS project data (Montero et al. 2011). Crop input costs and data (i.e. fertilisers, pesticides and energy consumption) are adapted from the same project by extending the crop period from 9 to 11 months (as mentioned above). Water consumption is calculated using the Fundación Cajamar software programme "PrHo v2.0 for irrigation systems of greenhouse horticulture" (González et al. 2008). Fertiliser and pesticide application includes their production as well as their emission into water and the atmosphere. Waste management accounts for transportation requirements for the disposal of crop system outputs, which are intended to be 100% recyclable, and recycling plants are located 30 km away from the site.

Because no experimental data are available to determine RTG tomato crop yields, a crop yield of 25 $kg \cdot m^{-2}$ is used as the reference yield in the assessment. This denotes the expected crop yield for a crop period of 11 months in a conventional greenhouse situated in the same geographic context (unpublished work, IRTA). Finally, the price at which producers sell tomatoes includes a 6 % margin in accordance with EUPHOROS project data (Montero et al. 2011).

Land costs (i.e. rooftop or agrarian soil use) are excluded from the economic assessment for two reasons. First, RTG business approaches are still unknown due to the lack of experiences in the study area. Consequently, prices are uncertain, as several rooftops may be owned by a single company that utilises the RTG (e.g. food companies) or may be rented to/by another agent. In this second case, the value of the rooftop may be determined as the urban soil price (which varies considerably depending on the location of the building), a lower price (e.g. a percentage of the soil price) or a value based on crop outputs. On the other hand, land costs are often excluded from economic balances of agriculture activities because land is an inversion that is presumed to be recovered when economic activity concludes.

*Conventional system: multi-tunnel greenhouse tomato production in Almeria (Spain)*

Inventory data and economic costs for tomato production in a multi-tunnel greenhouse in Almeria are obtained from EUPHOROS project data (Montero et al. 2011). The inventory is based on a crop yield of 16.5 $kg \cdot m^{-2}$.

### (iii) Assessment at the consumption point: a cradle-to-consumer perspective

Inventory data and tomato supply chain costs for a local RTG and conventional multi-tunnel greenhouse are detailed in the Appendix 2.6. The following section lists assumptions made for both systems throughout the data compilation process.

*Local supply-chain: RTG tomato production in Bellaterra*

The local supply chain accounts for residents of Barcelona that consume tomatoes produced in an RTG in Bellaterra. Tomatoes are transported by van (<3.5 t) from the production site to the consumption site (25 km). Tomatoes are packaged in trays made from recycled HDPE that weight 600 g each and hold 6 kg loads of tomatoes and which are recycled at the end of the lifespan, according to Sanyé-Mengual et al. (2013) and the packaging market (e.g. DAPLAST 2014). Finally, it is assumed that no product losses occur within the local supply chain due to the freshness of the product and limited manipulation of the product, which is sold immediately after harvesting.

*Conventional supply-chain*

The conventional supply chain for tomatoes grown in a multi-tunnel greenhouse in Almeria is based on Sanyé-Mengual et al. (2013). Conventional tomato distribution involves three steps. First, tomatoes are transported from the production site to a warehouse in Almeria (20 km). Second, tomatoes are transported to a food distribution centre in Barcelona (MercaBarna), where the tomatoes are sold to retailers (825 km). Third, retailers transport the product to their shops throughout Barcelona (10 km). Unlike the local supply chain, considerable product losses occur over the course of the conventional supply chain. Product losses occur during the transportation (due to dehydration) and retail stages (due to product damage). According to Sanyé-Mengual et al. (2013), total losses that occur throughout the Almeria-Barcelona tomato supply chain account for 16.6%. Supplying 1 kg of tomatoes at the consumption site necessitates a larger amount of agriculture production in a conventional supply chain than in a local supply chain, and this leads into higher associated environmental impacts and costs. Furthermore, damaged products in retail spaces are treated as a waste. For the purposes of this study, product losses that occur during the retail stage are assumed to be composted. In MercaBarna, electricity is used to light warehouse buildings. Finally, packaging practices are considered the same for both systems.

Data sources LCI data and costs for the different life cycle stages are obtained from various sources. Agricultural production data and costs provided correspond to data drawn from previous sections. LCI data on packaging production and transportation requirements are obtained from the ecoinvent database v2.2 (Swiss Center for Life Cycle Inventories 2010). The packaging cost is obtained from a distribution company of MercaBarna (*pers. comm.*, GavàGrup). Economic costs of the different stages are assumed as follows. Transportation costs are calculated according to the "Observatory of road freight transport costs in Catalonia" (Generalitat de Catalunya (DGTM) 2012). The average price of Spanish electricity (EUROSTAT 2014) is used as the cost of electricity consumption in the distribution centre. Composting, the treatment used to address food waste produced during the retail phase, is assessed based on LCI data drawn from the literature (Martínez-Blanco et al. 2011). Finally, the average price of tomatoes in Catalonia in 2013 (MAGRAMA 2014) is assumed to be the cost of product loss during the retail stage (Table 6.4).

### 6.3.3 Sensitivity analysis

Sensitivity analyses are performed to illustrate how results depend on two variables: crop yield and distance to conventional production site.

*Sensitivity analysis: crop yield variability (cradle-to-farm gate)*

As mentioned above, RTG crop yields in Mediterranean contexts are still unknown due to a lack of experimental data. On one hand, crop yields may decrease due to limitations, such as shadows generated by the structure. On the other hand, an i-RTG greenhouse can utilise residual building heat via air-flow exchange. This air has different temperature and $CO_2$ concentration that may benefit the agricultural production by increasing the crop yield (Cerón-Palma et al. 2012). Thus, a sensitivity analysis that accounts for various RTG crop yield levels is conducted to observe dependence results and trends. The analysis is applied to the production point assessment (cradle-to-farm gate), and crop yields range between 10 and 55 $kg \cdot m^{-2}$, the latter representing the Dutch crop yield value for tomato production in Venlo greenhouses (Montero et al. 2011). For conventional production (i.e. multi-tunnel), crop yield is considered constant as 16.5 $kg \cdot m^{-2}$ since experimental data is available. As variability on crop yield is mostly based on technological aspects (e.g. benefits from i-RTGs), crop inputs do not depend on crop yield while are considered as a determined application per area (e.g. amount of fertilizer per area of crop) rather than marginal consumption per amount of production.

*Sensitivity analysis: crop yield and distance to conventional production site (cradle-to-consumer)*

One advantage of RTGs is their urban location and thus close proximity to consumers and limited transportation requirements. Furthermore, key aspects of supply chain environmental impact are related to distance: agriculture production, product loss, packaging use and food waste treatment.

In this sense, the RTG system is considered as a local horticultural production. A distance threshold is calculated to determine the distance at which the RTG system either becomes more environmentally friendly or less cost intensive than the multitunnel system. The distance threshold is obtained by matching the environmental impact and economic cost of 1 kg of tomatoes produced in an RTG at the consumer point with the environmental impact and economic cost of 1 kg of tomatoes produced in a multi-tunnel greenhouse (i.e. located at a distance of X) at the consumer point. This threshold allows one to determine whether RTGs may become local production systems that offer environmental and economic benefits. However, because the crop yield is determinant, the distance threshold is calculated for three crop yield scenarios: low yield (10 kg·m$^{-2}$), reference yield (25 kg·m$^{-2}$) and high yield (55 kg·m$^{-2}$).

To accomplish this task, a model is designed to predict the environmental impact of the conventional supply chain ($EI_{CSC}$) by establishing a relation between the environmental impact or economic cost of each life cycle stage and the distance from the production site to the consumption site. The model is shown in Equation 6.1.

$$(6.1) \qquad EI_{CSC} = (1 + PL_t \cdot d) \cdot EI_{AP} + (1 + PL_t \cdot d) \cdot EI_P + \frac{(1+PL_t \cdot d) \cdot d \cdot EI_T}{1000} + \frac{0.1 \cdot d \cdot EI_{FW}}{1000}$$

where $EI_{CSC}$ is the environmental impact of the conventional supply-chain per kg of consumed tomatoes, $EI_{AP}$ is the environmental impact of agricultural production (i.e., per kg of tomatoes produced), $EI_P$ is the environmental impact of packaging (i.e., per kg of packaged tomatoes), $EI_T$ is the environmental impact of transportation (i.e., per tkm), and $EI_{FW}$ is the environmental impact of food waste treatment (i.e., per kg of composted food waste). The constant $PL_T$ refers to product losses occurring during transportation, which is $8.25 \cdot 10^{-5}$ kg of tomatoes·km$^{-1}$, according to data provided by Sanyé-Mengual et al. (2013).

The same model is used to calculate the economic cost of the conventional supply-chain ($EC_{CSC}$) based on distance, according to Equation 6.2.

$$(6.2) \qquad EC_{CSC} = (1 + PL_t \cdot d) \cdot EC_{AP} + (1 + PL_t \cdot d) \cdot EC_P + \frac{(1+PL_t \cdot d) \cdot d \cdot EC_T}{1000} + \frac{0.1 \cdot d \cdot EC_{FW}}{1000}$$

### *6.3.4 Environmental impact and economic assessment*

The environmental impact assessment of the two systems is performed by applying the life cycle impact analysis (LCIA) stage. The SimaPro 7.3.3 programme (PRé Consultants 2011) is used to conduct the LCIA, which follows classification and characterisation steps determined as mandatory by the ISO 14044 regulation (ISO 2006a). The LCIA is carried out at the midpoint level, and methods applied include the ReCiPe (Goedkoop et al. 2009) and cumulative energy demand (CED) (Hischier et al. 2010). With respect to the ReCiPe, the hierarchical time perspective is considered, as recommended in the ILCD Handbook (EC-JRC 2010). In comparing the RTG to the conventional system, results are shown in relation to three indicators: the normalised ReCiPe value (Norm-ReCiPe, Pt), the global warming potential (GWP, kg of $CO_2$ eq.) (IPCC 2007) and the CED value (MJ).

A cost-benefit analysis (CBA) approach is applied for the LCC assessment. Hence, life cycle costs and revenues for each system are considered. Two indicators are used as follows: total cost (TC, €) and total profit (TP, €). The assessment progressively expands the system boundaries, and costs may be borne out of different actors (especially in the conventional system). Actors can have different perspectives of costs (Hunkeler et al. 2008; Swarr et al. 2011). The actor changes depending on the assessment perspective: the producer is the actor of focus for the cradle-to-farm gate, and the retailer is the actor in the case of cradle-to-consumer perspectives. Because 2013 is used as the assessment reference year, costs and prices collected for different years were updated to the present value based on the inflation rate (Appendix 2.3).

## 6.4. Results and discussion

### *6.4.1. Greenhouse structure assessment*

The results of the greenhouse structure assessment for the RTG and multi-tunnel greenhouse structures are shown in Table 6.3.

Because the RTG structure was noted as a potential limitation to the implementation of RTGs in the literature due to the environmental impact and economic cost (Cerón-Palma et al. 2012), the first component of the assessment was focused on the greenhouse structure. The RTG structure has an associated environmental impact per square metre and year of $3.30 \cdot 10^{-2}$ Pt of the normalised ReCiPe indicator, a global warming potential of 2.42 kg of $CO_2$ eq. and an energy demand of 44.0 MJ (Table 6.3). Among ReCiPe indicators, the majority of the system's environmental impacts are associated with the materials and maintenance stages. Materials represent between 29 and 97.1% of environmental impacts generated by the system and 42.4% of the total cost, and maintenance represents between 3 and 70.6% of environmental impacts and 54.9% of the total cost. The material stage is the largest contributing one to the toxicity categories (58–95%), due to steel manufacturing processes and related air emissions of mercury and water emissions of manganese and arsenic. Maintenance stage is more impacting in those categories related to fossil resources, such as GWP, mainly due to the production of polycarbonate and consequent emissions of carbon dioxide and methane. Detailed ReCiPe results are shown in the Appendix 2.7.

***Table 6.3.*** *Environmental impact assessment and economic cost of the RTG structure, by life cycle stage, and comparison with the multi-tunnel structure, for a functional unit of 1 m2 of a greenhouse structure for a timeframe of 1 year.*

| | Norm-ReCiPe [Pt] | GWP [kg $CO_2$ eq] | CED [MJ] | TC [€] | TP [€] |
|---|---|---|---|---|---|
| **Rooftop Greenhouse (RTG)** | **3,30E-02** | **2,42E+00** | **4,40E+01** | **11,9** | **0** |
| Materials | 2,97E-02 | 1,02E+00 | 1,98E+01 | 5,02 | - |
| *- Steel [%]* | *96,4* | *69,5* | *75,6* | *62,2* | - |
| *- Polycarbonate (PC) [%]* | *2,2* | *26,8* | *19,7* | *5,3* | - |
| *- Polyethylene (PE) [%]* | *0,1* | *1,5* | *2,8* | *21,3* | - |
| *- Climate screen [%]* | *0,1* | *1,3* | *1,2* | *11,2* | - |
| *- Concrete [%]* | *1,0* | *0,8* | *0,8* | *0,1* | - |
| Construction | 1,71E-06 | 1,40E-04 | 3,94E-03 | 0,32 | - |
| Maintenance | 3,28E-03 | 1,39E+00 | 2,41E+01 | 6,51 | - |
| *- Polycarbonate (PC) [%]* | *77.4* | *75.2* | *58.9* | *16.2* | - |
| *- Polyethylene (PE) [%]* | *17.4* | *16.8* | *33.1* | *6.0* | - |
| *- Climate screen [%]* | *5.1* | *8.0* | *8.0* | *77.7* | - |
| End of life | 3,18E-05 | 7,74E-03 | 1,29E-01 | n.d. | - |
| **Multi-tunnel (M)** | **2,81E-02** | **1,38E+00** | **3,04E+01** | **4,26** | **0** |
| *- Steel [%]* | *91,7* | *39,6* | *29,7* | - | - |
| *- Polycarbonate (PC) [%]* | *1,1* | *10,1* | *6,6* | - | - |
| *- Polyethylene (PE) [%]* | *3,3* | *27,9* | *45,9* | - | - |
| *- Polyvinylchloride (PVC)[%]* | *0,5* | *2,7* | *3,5* | - | - |
| *- Polypropylene (PP) [%]* | *0,5* | *3,6* | *5,9* | - | - |
| *- Concrete [%]* | *0,8* | *8,0* | *2,0* | - | - |
| *- Transportation [%]* | *2,0* | *8,1* | *6,4* | - | - |
| **Ratio RTG/M** | **1,17** | **1,75** | **1,45** | **2,79** | **0** |

**Environmental indicators: Normalised-ReCiPe (norm-ReCiPe), Global Warming Potential (GWP), and Cumulative Energy Demand (CED; Economic indicators: Total cost (TC) and Total profit (TP).*

RTG structure materials contribute differently to the indicators and life cycle stages shown in Table 6.3. Steel is the material that has the largest environmental impact (69.5– 96.4%), followed by polycarbonate (2.2–26.8%) particularly in those categories where thermoplasts tend to have the most significant impact. Concrete only marginally affects the different indicators (<1%). During the maintenance stage, polycarbonate has the largest environmental impact of all of the materials (58.9–77.4%).

The RTG structure has a higher environmental impact than the multi-tunnel greenhouse structure: 17% of the normalised-ReCiPe, 45% of the CED, and 75% of the GWP (Table 6.3). However, differences between the two structures depend on the indicators, which are determined by the amount and type of materials used. With respect to the amount of materials, the RTG structure requires only 13% more material than the multi-tunnel structure (see the LCI value reported in the Appendix 2.4), and thus, one may assume that the environmental impact and economic cost of the RTG structure would be approximately 13% higher than that of the multi-tunnel structure. However, as the differences are more significant, it is necessary to examine the different types of materials. The most significant difference between the RTG and multi-tunnel structures is the volume of polycarbonate used: the first consumes 14 times more polycarbonate than the multi-tunnel. Consequently, RTG has a larger environmental impact in those categories in which thermoplasts contribute more, such as GWP (75% higher), than in other categories, such as human toxicity (6% higher).

The results of the economic assessment show that the total cost reaches 11.9€·$m^{-2}$·$year^{-1}$. The most expensive life cycle stage is the maintenance stage, which involves the substitution of plastic elements. Regarding materials, steel is the most expensive material (62.2%), although the climate screen is the most expensive element of the maintenance stage (77.7%). Furthermore, no profits are obtained from the greenhouse structure itself. Consequently, the cradle-to-grave economic cost of the RTG structure is 2.8 times larger than that of the multi-tunnel structure (Table 6.3). Detailed cost data are shown in the Appendix 2.7.

### *6.4.2. Assessment at the production point: cradle-to-farm gate perspective*

The RTG and multi-tunnel greenhouse tomato production results are compared in Table 6.4. At the farm gate, the production of 1 kg of tomatoes in a RTG has an environmental impact of $1.66\cdot10^{-3}$ according to the normalised ReCiPe indicator, a GWP of 216 g of $CO_2$ eq. and a CED of 3.25 MJ (Table 6.4). The greenhouse structure contributes the most to the ReCiPe indicators (41.0–79.5%), apart from four: marine ecotoxicity, in which nitrate emissions from fertiliser application have the main effect (95.4%); natural land transformation, in which substrate production contributes the most (53.8%); ionising radiation, in which irrigation system electricity consumption is the main contributor (50.9%), and agricultural land occupation, in which waste management contributes the most (34%). Detailed ReCiPe results are shown in the Appendix 2.8.

RTG tomato production has a lower environmental impact than conventional multi-tunnel production: GWP (9%), CED (14%) and Norm-ReCiPe (26%). These results differ from those of the greenhouse structure assessment because the RTG crop yield is expected to reach 25 kg·$m^{-2}$ due to the use of a larger crop period (11 months) than in conventional production (9 months). With respect to ReCiPe indicators, RTG tomato production has between 1 and 40%lower environmental impact than that of the multi-tunnel, with the exception of ozone depletion, on which RTG has a 30% higher impact due to plastic material production processes. RTG tomato production can notably decrease the water depletion potential of conventional production by 98%, as the system harvests rainwater from the top of the building as in the RTG-Lab. In addition, the agricultural land transformation impact is also reduced by 96% because RTGs are situated on rooftops, thereby alleviating pressures on agricultural areas. Nevertheless, impact distributions among production inputs are similar for both systems. Auxiliary equipment, which includes water and energy consumption, contributes the most to the normalised ReCiPe and cumulative energy demand (≈40%), although fertilisers contribute the most to global warming (≈53%) (Table 6.4).

At the farm gate, the economic cost of 1 kg of tomatoes produced in a RTG is 0.737€, and the total profit per kilogram is 0.045€. RTG tomato production is thus 21% more expensive than it is using the conventional system, mainly due to greenhouse structure costs. However, because profits are based on production costs (i.e. the sale price is calculated based on a 6% profit), RTG tomato production is more profitable than multi-tunnel tomato production (21%) (Table 6.4). RTG production costs are 18.4 €·$m^{-2}$ per production system area, to which the greenhouse structure contributes 63%. In contrast, multi-tunnel production costs reach 10.0 €·$m^{-2}$, and the greenhouse structure accounts for 43 %. For both systems, paid labour and fertilisers represent the other most significant inputs. Production costs per area are shown in the Appendix 2.5.

***Table 6.4.*** *Environmental and economic indicators of the tomato production and comparison with the production in a multi-tunnel system, for a functional unit of 1 kg of tomato at the farm gate, by life cycle stage.*

| | Norm-ReCiPe [Pt] | GWP [kg $CO_2$ eq] | CED [MJ] | TC [€] | TP [€] |
|---|---|---|---|---|---|
| **Rooftop Greenhouse (RTG)** | **1.66E-03** | **2.16E-01** | **3.25E+00** | **0.737** | **0.044** |
| Greenhouse structure | 1.15E-03 | 8.81E-02 | 1.60E+00 | 0.476 | - |
| Production inputs | 5.12E-04 | 1.28E-01 | 1.65E+00 | 0.128 | - |
| *-Auxiliary equipment [%]* | *43.0* | *18.5* | *41.0* | *40.1* | - |
| *-Substrate [%]* | *21.1* | *20.3* | *27.5* | *19.5* | - |
| *-Fertilisers [%]* | *16.0* | *52.3* | *19.3* | *25.5* | - |
| *-Pesticides [%]* | *4.6* | *1.0* | *1.6* | *14.9* | - |
| *-Waste management [%]* | *15.4* | *7.9* | *10.6* | *0.0* | - |
| Labour | - | - | - | 0.133 | - |
| Revenues | - | - | - | - | 0.781 |
| **Multi-tunnel (M)** | **2.25E-03** | ***2.37E-01*** | ***3.78E+00*** | ***0.607*** | ***0.036*** |
| Greenhouse structure | 1.72E-03 | 8.38E-02 | 1.84E+00 | 0.260 | - |
| Production inputs | 5.38E-04 | 1.53E-01 | 1.93E+00 | 0.183 | - |
| *-Auxiliary equipment [%]* | *40.2* | *17.1* | *39.2* | *34.6* | - |
| *-Substrate [%]* | *30.4* | *25.7* | *35.6* | *24.2* | - |
| *-Fertilisers [%]* | *18.8* | *54.0* | *20.4* | *26.0* | - |
| *-Pesticides [%]* | *6.6* | *1.3* | *2.1* | *15.2* | - |
| *-Waste management [%]* | *3.9* | *1.9* | *2.6* | *0.0* | - |
| Labour | - | - | - | 0.164 | - |
| Revenues | - | - | - | - | 0.643 |
| **Ratio RTG/M** | **0.74** | **0.91** | **0.86** | **1.21** | **1.21** |

**Environmental indicators: Normalised-ReCiPe (norm-ReCiPe), Global Warming Potential (GWP), and Cumulative Energy Demand (CED; Economic indicators: Total cost (TC) and Total profit (TP).*

### *6.4.3. Assessment at the consumption point: a cradle-to-consumer perspective*

Table 6.5 shows the results of the tomato production assessment at the consumption point in Barcelona for a local RTG supply chain from Bellaterra and a conventional supply chain from Almeria.

***Table 6.5.*** *Environmental and economic indicators of the tomato supply chain and comparison with the conventional supply-chain (multi-tunnel), for a functional unit of 1 kg of tomato at the consumer, by life cycle stage.*

| | **Norm-ReCiPe [Pt]** | **GWP [kg $CO_2$ eq]** | **CED [MJ]** | **TC [€]** | **TP [€]** |
|---|---|---|---|---|---|
| **Rooftop Greenhouse (RTG)** | **2.94E-03** | **7.08E-01** | **8.44E+00** | **0.863** | **0.607** |
| Agriculture production | 1.66E-03 | 2.16E-01 | 3.25E+00 | 0.752 | - |
| Packaging production | 1.28E-03 | 4.92E-01 | 5.19E+00 | 0.105 | - |
| Distribution | 3.72E-07 | 4.74E-05 | 8.26E-04 | 0.006 | - |
| Retail | - | - | - | - | - |
| Revenues | - | - | - | - | 1.47 |
| **Multi-tunnel (M)** | **5.11E-03** | **1.54E+01** | **1.39E+01** | **1.086** | **0.384** |
| Agriculture production | 2.63E-03 | 2.76E-01 | 4.41E+00 | 0.750 | - |
| Packaging production | 1.50E-03 | 5.74E-01 | 6.05E+00 | 0.123 | - |
| Distribution | 8.94E-04 | 1.94E-01 | 3.27E+00 | 0.067 | - |
| Retail | 9.41E-05 | 1.46E-02 | 2.14E-01 | 0.147 | - |
| Revenues | - | - | - | - | 1.47 |
| **Ratio RTG/M** | **0.58** | **0.67** | **0.61** | **0.79** | **1.58** |

**Environmental indicators: Normalised-ReCiPe (norm-ReCiPe), Global Warming Potential (GWP), and Cumulative Energy Demand (CED; Economic indicators: Total cost (TC) and Total profit (TP).*

At the consumption point, the life cycle of 1 kg of tomatoes produced in a local RTG has an environmental impact of $2.94 \cdot 10^{-3}$ in the normalised ReCiPe indicator, a GWP of 0.78 kg of $CO_2$ eq. and a CED of 8.44 MJ (Table 6.5). The agricultural production stage contributes the most to the normalized ReCiPe indicator (56.4%), while packaging contributes the most to GWP (69.5%) and CED (61.5%). For the other ReCiPe indicators, packaging is the most important life cycle stage (51.6–86.0%), apart from metal depletion, for which agriculture production (i.e. greenhouse structure) represents 58.7% of the impact; marine ecotoxicity, for which agriculture production (i.e. fertilisers) exhibits the highest impact (90.5%); and other toxicity indicators, for which agricultural production (i.e. emissions from metal production) represents the most influential stage (55.0–66.4%). Transportation from Bellaterra to Barcelona has a minimal (<1%) environmental impact. Trends are slightly different with respect to economic cost, for which agricultural production represents 87.1%, packaging represents 12.2% and transportation accounts for 0.7%. The cost distribution is mainly dependent on the greenhouse structure cost during the agricultural production stage. A reusable packaging scenario in which packaging is reused 20 times was quantified to further assess the environmental impact of local RTG tomato production. In this case, packaging becomes the second most influential contributor (between 1 and 18% of the impact), and agricultural production instead emerges as the most impactful stage. Overall, the impact of the local tomato supply chain can be reduced by between 32 and 82% (apart from marine ecotoxicity, 9%). The cost at the consumer point can also be reduced by 12%. Results are detailed in the Appendix 2.9.

Locally supplied RTG tomatoes have an environmental impact that is between 33 and 42% lower than tomatoes produced through the conventional supply chain, depending on the indicator. The economic cost of the RTG supply chain is also lower for each kilogram of tomatoes (21%) (Table 6.5). Among ReCiPe indicators, environmental savings reach between 20 and 74%, with the exception of water depletion, for which the use of rainwater boosts environmental impact reductions to 93%, although rainwater harvesting can also be used as a sustainable source of irrigation water for conventional greenhouses. Finally, the economic profits of RTGs are higher when the same tomato price for both systems (1.47€) is assumed. A local RTG supply chain obtains profits 1.58 times higher than the conventional supply chain (Table 6.5). These results are related to the following factors. First, RTGs follow a local supply chain in which transportation is largely reduced. Second, food waste is avoided in the RTG supply chain as the product is sold immediately after harvesting. As a result, additional tomato production is not needed to satisfy the 1-kg demand in the RTG scenario. These results assume the use of single-use packaging for both systems. However, packaging practices were assessed for both systems by comparing single-use and re-usable (20 uses) packaging options. When both systems use re-usable packaging, RTGs are still 21% cheaper than the conventional supply chain and have a lower environmental impact (between 36 and 98%). Sanyé-Mengual et al. (2013) noted that local systems have a higher capacity to reuse packaging than conventional systems. The environmental impact of a RTG local supply chain that uses re-usable packaging was thus compared to the results for a conventional supply chain that uses single-use packaging. In this case, local RTG tomatoes have a 41 to 98% lower environmental impact than the conventional scenario and are 30% cheaper (results are shown in the Appendix 2.9).

### *6.4.4. Sensitivity analysis: crop yield variability*

An agricultural production system has an associated environmental impact per area that is allocated for each kilogram of product based on the crop yield. For the RTG system, a crop variability sensitivity analysis was conducted due to high levels of uncertainty surrounding crop yields. Results in Fig. 3 show the same pattern for the three environmental indicators and for the economic cost. At the farm gate, 1 kg of tomatoes produced in an RTG has the same environmental impact as 1 kg of tomatoes produced in a multi-tunnel greenhouse when crop productivity reaches between 20.3 and 23.7 $kg \cdot m^{-2}$, depending on the indicator. Regarding economic costs, the crop yield can be increased further to 30.4 $kg \cdot m^{-2}$.

Although RTG tomato production in the reference scenario (25 $kg \cdot m^{-2}$) is associated with lower environmental impacts but slightly higher economic costs than those of conventional greenhouses, two trends can be found in the sensitivity assessment (Figure 6.3). First, very low RTG yields (<15) (e.g. due to shadows from other buildings or the greenhouse structure on crops) can result in expensive food products of high environmental impact. On the other hand, i-RTGs can utilise residual building air (heat and $CO_2$), thereby increasing RTG crop yields without enlarging environmental burdens. Consequently, food products grown in i-RTGs that reach high yields (>40) may be of considerable interest due to their low environmental impact and economic competitiveness. These findings contribute to the existing debate on the pros and cons of local production in relation to conventional options (Edwards-Jones et al. 2008).

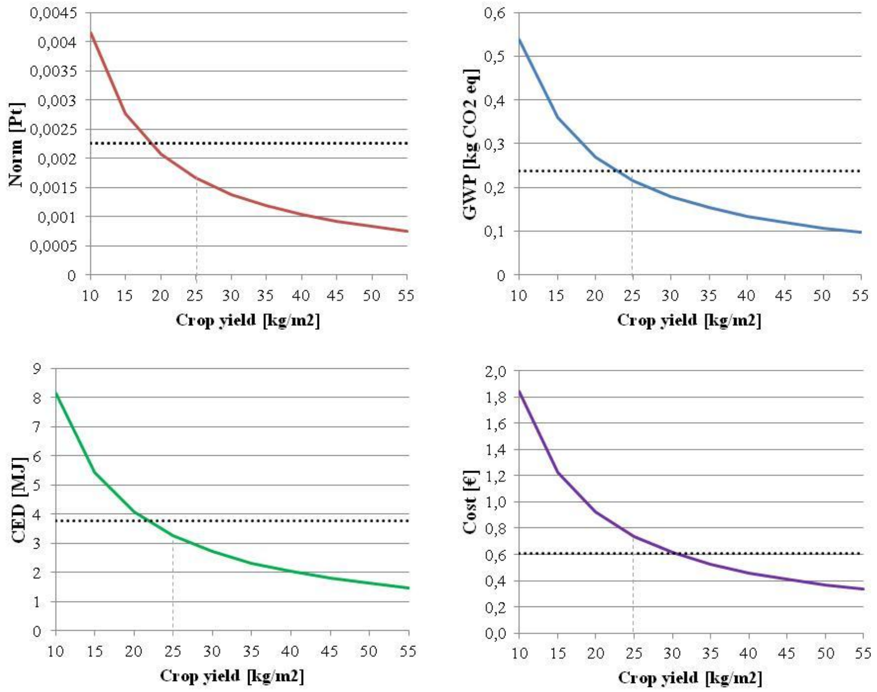


***Figure 6.3.*** *Sensitivity analysis of the environmental indicators related to the crop yield variability. Solid line indicates the indicator value, and the dotted line indicates the indicator value for the reference system: tomato produced in a multi-tunnel greenhouse (constant crop yield of 16.5 kg·m*$^{-2}$*).*

Regarding potential economic benefits, a local producer (e.g. RTGs) can capitalise on retail options that avoid supply chain agents (i.e. direct selling to consumers). RTG businesses are in a particular optimal position to sell their products through different venues, as shown in the following examples: Gotham Greens sells products in supermarkets, Lufa Farms distribute horticultural products through a community supported agriculture (CSA) model and The Vinegar Factory operates its own specialty store. When calculating the minimum tomato price necessary to cover RTG production costs by crop yield, it becomes evident that RTG-grown tomatoes can be sold at prices even lower than the producer tomato price (0.61€) (updated from Montero et al. 2011) (Figure 6.4).

With respect to the reference scenario, an RTG with a crop yield of 25 kg·m$^{-2}$ could cover production costs by adopting a tomato price lower than the current retail price (1.47€) and could thus become more competitive by selling tomatoes at prices lower than the current wholesale price (1.18€). However, as shown in the sensitivity analysis listed in Fig. 4, these results strongly depend on crop yields (detailed information is provided in the Appendix 2.10).

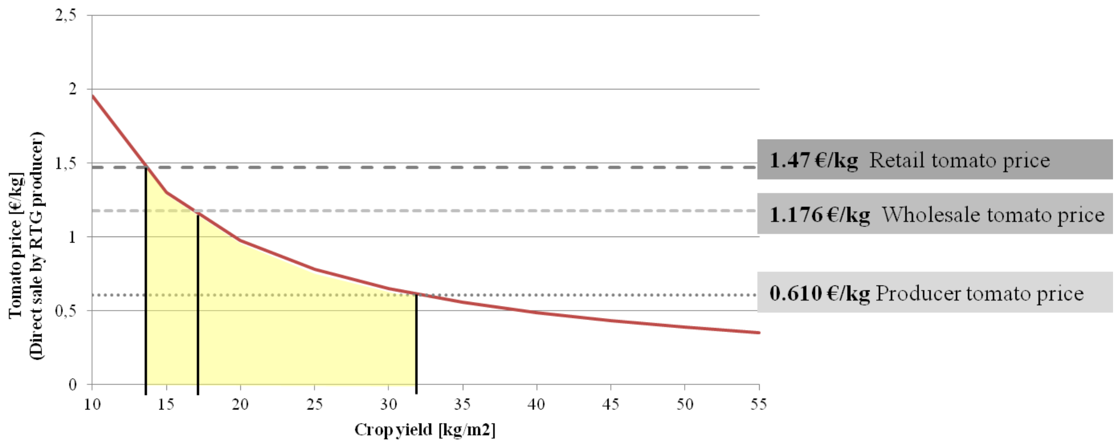


***Figure 6.4.*** *Sensitivity analysis of the minimum tomato price to cover RTG production costs and comparison to current tomato prices in the market, by crop yield.*

### *6.4.5. Sensitivity analysis: crop yield and distance to conventional production site*

The environmental impact and economic cost of conventional supply chain (i.e. multi-tunnel) tomato production is calculated for a transportation distance of 0 to 1000 km. Through a comparison between local RTG tomato values, one can determine the distance at which local tomatoes are better to conventional tomatoes in environmental and economic terms. Figure 6.5 shows comparisons for the four indicators.

With respect to the reference yield (25 kg·m$^{-2}$), local RTG tomatoes exhibit a superior environmental profile than tomatoes grown from conventional production. Otherwise, local tomatoes are more expensive than conventional tomatoes due to costs associated with the RTG structure. Consequently, RTG tomatoes will only become cheaper than conventional tomatoes when grown in an area at least 400 km away from Barcelona. In the case of i-RTGs with high yields (55 kg·m$^{-2}$), tomatoes from local RTGs would be preferable to conventional options with respect to both environmental and economic indicators (Figure 6.5).

In contrast, local tomatoes grown from low-yield RTGs (10 kg·m$^{-2}$) would need to substitute conventional tomatoes from areas situated between 120 and 870 km to become more environmentally friendly. Distances depend on the indicator considered as follows: 120 km (ReCiPe-norm), 650 km (GWP) and 870 km (CED). These results demonstrate how the definition of environmental products affects results. Current eco-labels typically focus on the global warming or energy consumption impacts of products, such as carbon footprint labelling used in Tesco supermarkets. In this case, local RTG tomatoes may be superior to other local products (<100 km) from a global environmental perspective (i.e. ReCiPe-norm indicator), but worse than other products when focusing on certain aspects (i.e. GWP or CED). Consequently, the prioritisation of indicators can significantly affect how environmentally friendly local products are relative to other market options. Finally, local tomatoes grown in low-yield RTGs will not become cheaper than tomatoes grown via conventional production in Spain (Figure 6.5).

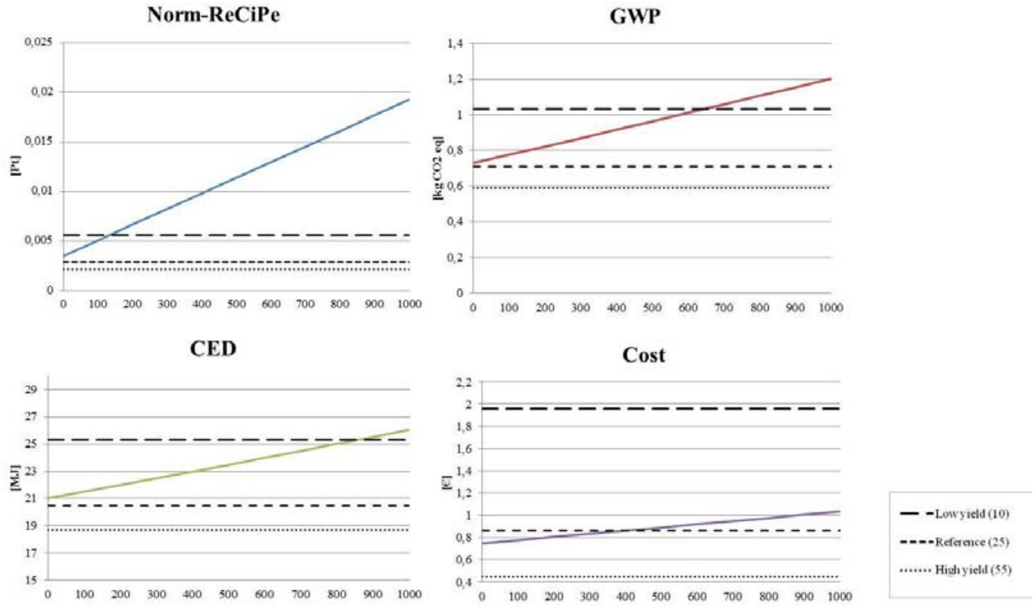


***Figure 6.5.*** *Environmental and economic indicators for 1 kg tomato from a conventional supply-chain at the consumption point by transported distance, and comparison with the value of 1 kg of tomato from local RTGs with a low yield (10 kg·m$^{-2}$), reference yield (25 kg·m$^{-2}$), and high yield (55 kg·m$^{-2}$).*

## 6.5. Conclusions

The paper contributes to the current theoretical knowledge of building-based urban agriculture (Despommier 2010; Cerón-Palma et al. 2012; Specht et al. 2014; Thomaier et al. 2015). This assessment from the greenhouse structures to the final products provided a comprehensive understanding of the environmental and economic performance of RTGs in the Barcelona area. Comparisons with conventional greenhouse systems contextualised the results within the current agriculture sector. The assessment found that the RTG infrastructure has a larger environmental impact and is more expensive than a multi-tunnel system. However, tomatoes produced in RTGs have a lower environmental impact than those produced in multi-tunnel greenhouses, both at the farm gate and at the point of consumption. In contrast, RTG-grown tomatoes are more expensive at the farm gate, but cheaper at the point of consumption, when all the supply chain costs are included.

At the greenhouse structure level, RTGs have greater environmental impacts than multi-tunnel greenhouses (between 17 and 75%), though economic costs associated with the former were 2.8 times higher. Therefore, at the greenhouse structure level, RTGs are less attractive than multi-tunnel greenhouses from an environmental and economic perspective. These results reiterate risks and limitations associated with RTGs that have been previously mentioned in the literature (Cerón-Palma et al. 2012; Specht et al. 2014). The present study assessed a pilot project that was adapted to current building legislation and which exhibited higher resources consumption than conventional greenhouse systems. However, future efforts may balance legislative requirements with innovation by, for instance, limiting greenhouse structure overweighting.

As horticultural production systems, RTG and multi-tunnel greenhouse tomato production systems were compared. At the production point (cradle-to-farm gate), 1 kg of RTG-grown tomatoes had an environmental impact between 9 and 26% lower than that of the multi-tunnel system. The economic cost of RTG tomatoes was 21% higher than associated multi-tunnel cost, although the RTG system obtained a 21% higher profit. Differences between RTG and conventional system production were based on crop yields. Crop yields were higher in the RTG than in the multi-tunnel greenhouse system because RTGs are designed to combine two crop cycles in a single year, resulting in a crop yield of 25 $kg \cdot m^{-2}$. At the consumption point (cradle-to-consumer), tomatoes locally produced through RTGs in Bellaterra had a lower environmental impact and were cheaper than those produced through conventional supply chains originating from Almeria. More specifically, the environmental impact was between 33 and 42% lower and the cost was 21% cheaper. These results vary depending on the extent to which local produce distribution and food waste production are avoided. Furthermore, the type of packaging (single-use or reusable) can affect the results significantly.

Crop yield variability was found to significantly affect assessments of these new systems. First, no experimental data exist to determine the real RTG crop yield for the Mediterranean context. Second, i-RTGs are expected to increase crop yields without increasing environmental burdens or economic costs. Consequently, the sensitivity assessment showed potential variations in the environmental impacts and economic costs of RTGs. When considering the entire supply chain, the balance between local, RTG-grown products and conventional products strongly depends on the crop yield. Local RTGs with high crop yields (>25 $kg \cdot m^{-2}$) may produce tomatoes with lower environmental impact than conventional supply chains. Thus, the agronomic efficiency of each RTG project will determine whether RTGs are superior to conventional systems in environmental and economic terms.

### *6.5.1. RTGs contribution to urban agriculture and sustainability: economic and social aspects*

Overall, RTGs promote sustainable urban agriculture by addressing key aspects of environmental policy: energy consumption and global warming. As local production systems, RTGs offer sustainable distribution practices by limiting food miles and associated environmental impacts. Furthermore, environmental benefits are not only found in distribution stages due to reduced distances but also along the entire life cycle of the product: in initial stages, lower product loss in distribution results in a reduction in agricultural production, while in final stages, this also derives in a smaller amount of food waste. In addition, i-RTGs that exchange energy flows with buildings can minimise energy consumed through both agricultural production and building operation (e.g. reduced heating demand) (Cerón-Palma 2012).

RTGs and urban vertical farming strategies can effectively supplement the urban self-supply of food through local consumption (Cerón-Palma et al. 2012; Specht et al. 2014). Local production should only complement the conventional agricultural sector, which currently serves the vegetable market. However, local production schemes such as RTGs can address the growing demand for local products. Moreover, some RTG projects have focused their production on added-value options, such as producing marmalade or offering off-season products at a competitive price. Even more, RTGs can take advantage of their situation by producing vegetables that are prone to spoilage during transportation. Furthermore, urban agriculture will contribute to the green economy, which represents one of the key features of sustainability policies applied in developed countries (UNEP 2011b). For instance, the European Commission published the communication “Towards a circular economy: a zero waste programme for Europe” for establishing a common and coherent EU framework to promote the circular economy (European Comission 2014), given its potential to enhance and diversify the economy while also creating quality jobs (UNEP 2011b). However, a hypothetical boost of local products could disrupt the current conventional sector, leading into a decrease in national demand. This effect could cause a decrease in the sector (e.g. job loss) or an increase in national exportation to maintain production, thereby originating an environmental re-bound effect due to increased transport distances.

### *6.5.2. Limitations of the study and further research*

This study exhibits a number of limitations related to the incipient implementation of RTGs and lacking data available on this issue. First, this study considers the lifespan of the RTG structure to be 50 years, according to project data and information provided by architects and engineers. However, environmental characteristics associated with greenhouses (e.g. humidity) may reduce the lifespan or other features of an RTG, thereby increasing maintenance requirements and associated environmental impacts and economic costs. Second, a lack of experimental data on existing RTGs in the Mediterranean area resulted in crop yield uncertainty. This was a weakness of the study, which was solved by adding a sensitivity analysis to the assessment. Nevertheless, RTG crop yield values will determine the environmental impact and economic costs of local RTG vegetables. Moreover, further sensitivity assessments may include crop yield variability of conventional technologies. Third, the assessment of RTG tomato production uses 1 $m^2$ of productive area to analyse both the RTG and the multi-tunnel systems as commercial activities. However, RTGs use space in a less efficient manner than conventional greenhouses due to an imbalance in the scale of activities: while the RTG examined in this study occupies 122.8 $m^2$, the multi-tunnel greenhouse occupies nearly 2 ha. Finally, although the RTG-Lab will focus on the exchange of flows between greenhouses and buildings (i-RTGs), the study does not consider the metabolic interconnection and infrastructure requirements needed for this purpose.

Further research on new forms of urban agriculture and on rooftop greenhouses in particular may focus on the following issues. First, agronomic data on existing RTGs will reduce result variability related to crop yields. Second, i-RTGs that exchange energy, water and gases may shed light on the metabolism of such as structure and associated agronomic, environmental and economic advantages. Third, an environmental and economic assessment of local production systems and other urban agriculture systems may provide a more nuanced contextualisation of RTGs within this sector. Furthermore, studies may pay additional attention to potential uses of RTG models. Other applications may include the development of private, commercial RTGs or public RTGs for community use. Finally, social indicators should be included in future studies on RTGs.

# Chapter 7

## Environmental analysis of the logistics of agricultural products from Rooftop Greenhouses in Mediterranean urban areas.

Picture: *Packaged fruits and vegetables in Mercabarna (Barcelona, Spain)*

*(©Júlia Martínez Blanco)*

# Chapter 7

This chapter is based on the journal paper:

> Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, Montero JI, Rieradevall J (2013) Environmental analysis of the logistics of agricultural products from Roof Top Greenhouse (RTG) in Mediterranean urban areas. *Journal of the Science of Food and Agriculture* 93(1): 100–109 (DOI: 10.1002/jsfa.5736).

## Abstract

As urban populations are increasing as well as the food transported to cities worldwide, innovative agrourban systems are being developed to integrate the agricultural production into buildings, such as Roof Top Greenhouse (RTG). This chapter aims to quantify and compare, through a Life Cycle Assessment, the environmental impact of the current linear supply system to the RTG system using a case study for the production of tomatoes.

Main results indicate that the change from the current linear system to the RTG system could result in a reduction, per kg of tomato (functional unit), in the range of 44.4 to 75.5% for the different impact categories analysed, and savings of up to 73.5% in the energy requirements. These savings are associated with the reutilization of the packaging systems (55.4 – 85.2%), the minimization of the transport requirements (7.6 – 15.6%) and the reduction of the losses of product during transportation and retail (7.3 – 37%).

RTG may become a strategic action in the design of low carbon cities in Mediterranean areas. A short-term implementation in the city of Barcelona could result in savings of 66.1 tonnes of $CO_2$ eq. per ha and of 71.03 tonnes considering the land transformation avoided.

Keywords: rooftop greenhouse, transport, agrourban systems, agrifood sector, LCA.

## 7.1. Introduction

Cities play a key role in the global environment as they are dependent on external sources of energy and goods (Girardet 2010). Moreover, urban areas contain 50.6% of the world population, and it has been estimated that this number will continue to increase to 70% by 2050 (UN-Habitat 2010). As food is a basic human need, urban food access has become a key issue for the sustainability of cities.

Urban expansion has several consequences for food security (FAO 2011): land demand for housing, industry and infrastructure competes with agricultural production within and around cities. Additionally, due to an increase in the quantities of food consumed, the expansion of urban areas coupled with changes in consumption habits and food purchasing behaviour, has caused an increase in the number of food-loaded transports to cities. Freight is mainly transported by road, although airfreight and maritime transport have increased during the last decade, mainly in developed countries (EEA 2010). Such changes could lead to an increase in traffic congestion and air pollution as well as putting additional stress on existing food distribution infrastructure and facilities (FAO 2011). Furthermore, production could also be affected by the rise of the real energy prices, as the cost of inputs and transport and the demand for agricultural products as feedstock for biofuel production will increase (FAO 2010).

### *7.1.1. Environmental studies in agri-food distribution systems*

Agrifood production areas are usually not in close proximity to cities. This has made the distribution stage of agricultural products an area that has considerable opportunity for reducing the environmental impact of cities. It is, thus, essential to optimize the efficiency and dynamism of food supply-chains and distribution systems in order to increase the sustainability of cities (FAO 2011).

Previous studies have analysed different stages of the life cycle of an agrifood product. In specific, agriculture production received considerable attention as it was identified as a hotspot in the life cycle of food products (Roy et al. 2009). In addition to this, the research on agricultural production has also focused on raw materials and waste management (Martínez-Blanco et al. 2010), as well as on cultivation methodologies to improve the environmental profile of crops, such as organic farming (Meisterling et al. 2009).

Regarding the transport stages and the food supply-chain, Jones (2002) analysed the transport systems that existed for distributing dessert apples in the United Kingdom, from imported to local products and with different marketing systems. Differences between them were shown (from 0 to 17.75 MJ of energy consumed per kg of apples), including the transport consumption which was, in several cases, several orders of magnitude higher than food production.

Focusing on the differences between local and imported products, also for apples, Milà i Canals et al. (2007) highlighted great differences between production in Europe, South America and New Zealand, energy requirements of the storage stage and of specific farming practices, and the effect of the season of production and consumption. Moreover, the importance of transport for agricultural products exported from islands, such as Canary Island, was also analysed (Torrellas et al. 2008).

Moreover, local production and green shopping are trending topics towards new consumer behaviour and vegetables retail. As an example, a Swiss study (Tobler et al. 2011) concluded that environmental impact related to the distribution of vegetables is the most concerning life cycle stage from the consumers' viewpoint: a sample of almost 80 consumers identified transport distance, post-consumption treatment of packaging waste and production method as the main criteria when choosing environmental friendly vegetables.

In summary, the current distribution of agricultural products is a linear system that has logistic requirements mainly between countries or regions, and the related energy consumption and $CO_2$ emissions concern the vegetables consumers. Therefore, some green and farming systems have been developed recently in order to reduce the environmental impacts related to cities increasing the agricultural productivity of them. These incipient systems turn the urban logistics of agricultural products into a circular system, where products are produced and consumed in the same city.

### *7.1.2. Green and farming systems integrated in buildings of the cities*

The aforementioned green and farming projects have focused on harnessing the roofs and facades of buildings through green systems (Green Roof, Green Facade), with the aim of naturalizing cities, and cultivation systems (Rooftop Greenhouse), that are designed to produce food in the city. Green Roof systems are applied on the roof of buildings and offer several benefits for the buildings. Some of these benefits are an increase in the lifespan of the roof (Teemusk and Mander 2009), reducing in the energy consumption for heating and cooling buildings due to the thermal isolation (Saiz et al. 2006) and incrementing biodiversity of cities (Köhler 2008).

Beyond benefits for buildings, researchers have shifted their focus from Green Roofs to developing Urban Vertical Farming (UVF) systems as a new strategy that offers environmental, social and economic advantages. Instead of periurban agriculture with crops next to cities, UVF is an agrourban system that consists of producing agricultural products on building roofs. These systems can be applied in different ways: unprotected crops in roofs, protected crops in walls of skyscrapers and protected crops in roofs. Rooftop Greenhouses (RTG) are protected crops integrated in the rooftops of buildings with hydroponic intensive culture.

This study considers RTG crops based on hydroponic systems as agrourban system applied. Hydroponic methods are soil-less crops that use mainly inert substrates, such as perlite or rockwool. Irrigation in this system requires less amount of water, with savings of 30% and almost 50% in recirculating systems. Moreover, less chemicals inputs are needed due to a higher effectiveness as they are dissolved (Antón et al. 2005; Ecoponics project 2012). Furthermore, hydroponic systems mainly show higher productivity rates that strongly vary among different types of vegetables. For instance, Antón et al. (2005) reported a yield of 15 $kg\cdot m^{-2}$ for hydroponic cultivation against 11 $kg\cdot m^{-2}$ for soil cultivation of tomato production in unheated Mediterranean greenhouses. Some other authors (Muñoz et al. 2008) report yields up to 20 $kg\cdot m^{-2}$ for a summer tomato crop in hydroponic cultivation, while common yields for soil cultivation under the same climate conditions range between 14 and 16 $kg\cdot m^{-2}$ (Muñoz et al. 2008; Martínez-Blanco et al. 2011).

In addition, RTG systems are being designed to utilize waste heat, waste water and $CO_2$ flows from the building. These exchanges would benefit both subsystems in a synergic way, such as the use of waste heat for heating the greenhouse. However, this study analyses RTG systems without interconnection (Figure 7.1).

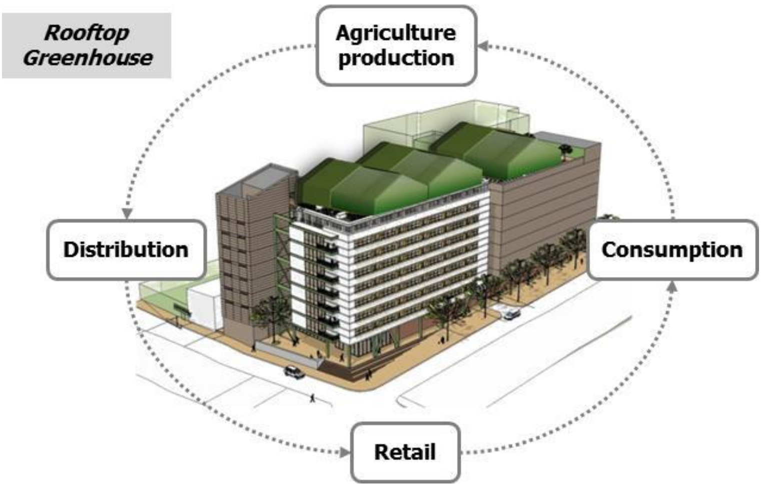


***Figure 7.1.*** *Rooftop Greenhouse systems, as a closed cycle for production and consumption of agricultural products in the cities.*

Beyond the benefits for the building and the biodiversity of the city, there are some advantages related to the food supply in RTG systems (Despommier 2010; Cerón-Palma et al. 2012):

- Reduction of transport requirements. As the production is commenced in cities, transport requirements for agricultural products would be lowered, as they drastically reduce or completely eliminate the distance between crop areas and cities.
- Reutilization of packaging. Agrourban systems open an opportunity for more sustainable packaging systems with a reduction in the quantity of materials and an increase of multi-way systems use as reutilization rates can be higher.
- Decrease in the loss of product. As a local product, the loss of product will be reduced due to a higher freshness of the products, which guarantees its conservation and the quality, and the reduction of the distribution requirements.

However, agrourban production is still an incipient field and very little quantitative data about its social, environmental and technological advantages are available.

Agrourban systems can be developed in Mediterranean cities without additional heating supply due to the climate context. This is different in Northern European cities where heat is required which, consequently, results in an increase in the energy demand. In order to avoid environmental impacts related to the distribution stage, RTG systems may play a significant role in key areas, such as the Mediterranean. Agrourban systems could positively influence the current compact morphology of Mediterranean cities. These systems could increase the cities' multifunctionality, as they represent a change in the urban model into a new symbiosis system between urban and agriculture.

Barcelona is an example of a city with a great potential for the application of RTG. As of 2009, there were 9.48 ha of Green Roof systems in the city (109 buildings), which could be an immediate implementation area for Urban Vertical Farming systems. A recent study has estimated the potential surface for implementing farming roofs in 95 ha of residential buildings, without considering industrial ones (BCN Ecologia 2010). Beyond the research of local and imported agricultural products, this chapter works in the comparison of regional agriculture to a new phenomenon of agricultural systems integrated into cities, considering a transformation of the linear model of food supply-chain to cities towards a more self-sufficient and circular model.

### *7.1.3. Goal and objectives*

The general aim is to test and quantify the environmental impacts related to the logistics of RTG systems and the current food supply system in Mediterranean urban areas through a comparative Life Cycle Assessment (LCA) of the production of tomato in the city Barcelona.

## 7.2. Materials and methods

LCA methodology was followed to quantify the environmental impacts related to the system. Life cycle inventory data was obtained through a local survey and European databases.

### *7.2.1. Environmental tools: Life Cycle Assessment (LCA)*

LCA (ISO 2006a) is the methodology followed to determine the environmental burdens of the scenarios. The identification and quantification of the main flows of the system, through a Life Cycle Inventory (LCI), is followed by the classification and characterisation steps. A classification step enables the association of each environmental load to one or more impact categories. Secondly, the characterisation is made for the overall impact, which is worked out by multiplying each load by a characterisation factor associated to each impact category. The classification and characterisation stages observe the CML-IA method (Guinée et al. 2002). The selected midpoint impact categories and their units are as follows: abiotic depletion potential (ADP, kg Sb eq.), acidification potential (AP, kg $SO_2$ eq.), eutrophication potential (EP, kg $PO_4^{3-}$ eq.), global warming potential (GWP, kg $CO_2$ eq.), ozone layer depletion potential (ODP, kg CFC-11 eq.) and human toxicity potential (HTP, kg 1.4-DB eq.), and Cumulative Energy Demand (CED, MJ) for the energy requirements flow.

#### (i) Local data

Local data was obtained for completing the LCI. Data for the transport of tomato from the producer to Almeria was obtained from Cajamar Fundation (Almeria). The distribution stage data from Almeria to MercaBarna, considering the mean of transport and the loss of product, was completed through an interview with the manager of one distribution firm specialized in tomato (Gavà Grup, in MercaBarna). Data of energy consumption in the distribution centre (MercaBarna) was supplied by its managers. The data for the transport from the distribution centre to retail, the loss of product in the retail stage and the packaging system was obtained through a survey on the retail stage that was made at 30 groceries randomly selected in the city of Barcelona.

The survey includes the following questions and possible answers:

- Transport from the distribution centre to retail: What type of vehicle is used for the transport of tomatoes to retail? (A. Car (<3.5 t), B. Van (<3.5 t), C. Truck (3.5 – 10 t), D. Others)
- Loss of product: Percentage wise, what is the loss of product during the retail stage? (A. <5%, B. 5 – 10%, C. 10 – 20%, D. >20%)
- Packaging: What is the packaging system used for tomatoes to be transported to the retail? (Open answer, specifying data about the material, the weight and the capacity)

### (ii) Global data

The ecoinvent 2.2. database is used as a source of information to calculate the impact of the energy production associated to the quantified consumption flow, transportation requirements and the impact of the materials of the inventoried packaging flow (Table 7.1).

***Table 7.1.*** *Specific global data sources used in the LCIA.*

| Flow | Source |
|---|---|
| Electricity mix for Spain | ecoinvent database 2.0 (Dones 2007) |
| Road freight transport | ecoinvent database 2.0 (Frischknecht et al. 2007) |
| Plastic production (packaging) | ecoinvent database 2.0 (Hischier 2007) |
| Cardboard production (packaging) | ecoinvent database 2.0 (Hischier 2007) |

### (iii) Study system

The study case is situated in the Mediterranean Area. For calculation purposes, RTG is considered to be installed in a building in Barcelona (Catalonia, Spain), as some studies have already studied the roof availability for this purpose (Ajuntament de Barcelona 2010; BCN Ecologia 2010). For the CLS scenario, it is estimated that the fresh tomato are imported from Almeria and locally distributed from MercaBarna, which is a food distribution centre situated in the same city in the logistics zone of the port of Barcelona.

Tomato is selected for the study because it is the second most widely sold product of MercaBarna (8.7% of selling in weight) and the first among those that can be cultivated in RTG systems; as potato cannot be cultivated in hydroponics culture system (without soil). The origin chosen is Almeria, the main origin for tomato imports in MercaBarna with almost 60% of the overall selling (MercaBarna 2011).

### (iv) Functional Unit

The functional unit selected for the LCA study is 1 kg of tomato delivered to the final consumer.

### (v) System boundaries

For comparative purposes, the system boundaries are delimited to the agricultural production, packaging production, distribution and retail stages, excluding the use stage as it has been considered the same for the two scenarios.

### *7.2.2. Life Cycle Inventory (LCI)*

The LCI for both scenarios are based on the following hypothesis:

- Hydroponic culture systems are selected for the production stage to design comparative scenarios.
- The same production infrastructure is considered for both systems, although the RTG production has not yet been studied in detail. However, different production yields are taken into account according to the climate conditions for both geographic regions and to the literature.

- Regarding the retail stage, tomato is sold in Barcelona through shops, such as groceries or municipal markets. The only environmental burden considered for this stage was the waste treatment of the damaged product. The electricity consumption of the building and the workers transportation were assumed equal for both scenarios and not included.
- The consumption stage was excluded as it is the same for both systems.
- The type of building (new, rehabilitated or old) was not considered in the analysis. Therefore, negative or positive impacts regarding the building issue are neglected, such as reinforcement structure requirements (for old buildings) or environmental benefits due to synergies between the greenhouse and the building (RTG flows' integration for new buildings).

### (i) Scenario CLS: Current Linear System

The CLS considers the life cycle of a tomato produced in Almeria, transported to Barcelona, and sold and consumed in Barcelona (Figure 7.2). The stages considered are the agricultural production, the distribution, the retail and the packaging production, as described below.

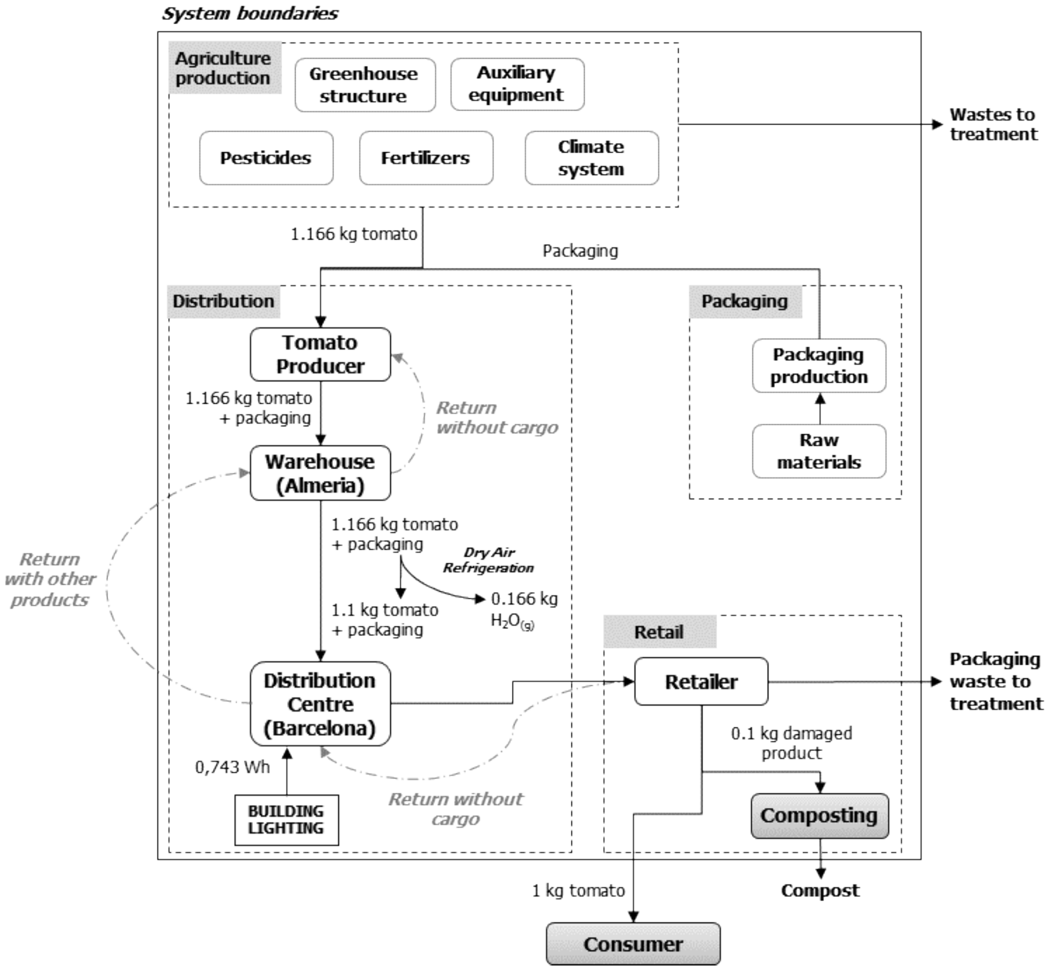


***Figure 7.2.*** *System description and boundaries for Scenario CLS (Current Linear System) of the logistics of tomato: from Almeria (production site) to Barcelona (consumption site) through a distribution centre.*

*Agriculture production.* Tomato agriculture production in Almeria is primarily done in a protected manner through multitunnel greenhouses with a productivity of 16.48 $kg \cdot m^{-2}$ of tomato per year (Montero et al. 2011). LCI data for this stage is obtained from the FP7 EU EUPHOROS project (Montero et al. 2011) and Torrellas et al. (2012). These works structured the LCA of the tomato production in five main subsystems (Figure 7.2):

- Greenhouse structure: an arched-roofed industrial steel-framed, multitunnel greenhouse is made of a steel frame and a LDPE plastic covering, wire systems to support the tomato crop, concrete foundations and paths.
- Auxiliary equipment: distribution system for watering the crop, drainage installation, pipes to collect rain water and substrate are considered auxiliary equipment, and the electricity and water consumption, as well as the perlite (substrate) production are included in the LCI.
- Climate control system: as there are no heating systems in this multitunnel greenhouse, only the electricity consumption for opening and closing ventilators are considered.
- Fertilizers: the quantity of Nitrogen, Phosphorous and Potassium needed for the crop is also evaluated. Air emissions are entailed in the calculation, according to the parameters proposed by Bentrup and Küesters (2000) for Ammonia and Audsley (1997) for Nitrogen oxides.
- Phytosanitary treatments (Pesticides): the use of insecticides and fungicides and its application through machinery are taking into account. Although the EUPHOROS project (Montero et al. 2011) excluded the toxicity effects from pesticides, in this study the impact factors from the CML-IA method (Guinée et al. 2002) were assumed to evaluate the toxicity impact related to pesticides' emissions.

*Distribution stage.* The current transport system for 1 kg of tomato to a consumer in Barcelona includes three trips: from the producer to a warehouse in Almeria, from Almeria to the distribution centre in Barcelona (MercaBarna) and from the distribution centre to the retailer (Figure 7.2). Note that during the Almeria - MercaBarna trip, there is a loss of 6% of the weight of the product as it is done in refrigerated trailers with dry air systems that imply evaporation of the product's humidity (Gavà Grup manager, *pers. comm.*).

Finally, there is an energy consumption corresponding to the lighting of the building of the Fruit and Vegetables Market, where tomatoes are sold in MercaBarna. The total electricity consumption for this purpose was of 772,000 kWh in 2010 (MercaBarna managers, *pers. comm.*) and a total amount of 1,039,293 tonnes of product was sold (MercaBarna 2011). Note that energy consumption for refrigeration purposes is not necessary for tomato (Gavà Grup manager, *pers. comm.*).

*Retail stage.* According to the survey about the retail stage in Barcelona, for Scenario CLS there is a product loss of 10% during this stage. The retail stage considers the composting of this loss of product. Organic wastes are transported (waste collection) and composted. LCI data for waste composting in Barcelona facilities is obtained from Martínez-Blanco et al. (2010). This work considered a full-scale composting treatment that uses the in-vessel (‘‘tunnel”) decomposition technology with a curing phase in turned windrows in an enclosed building.

*Packaging production.* The retail survey showed three packaging options for tomato: a plastic tray of high density polyethylene (HDPE), a cardboard box and a wooden box. However, the results indicate that the most used packaging is the plastic tray which is used in 80% of the establishments; while cardboard and wooden boxes are used in a share lower than 50%. Therefore, the HDPE tray has been selected for the analysis. Data for the LCI was obtained from the ecoinvent database.

### (ii) Scenario RTG: RTG system in Barcelona

The RTG system considers the life cycle of a tomato produced and consumed in Barcelona (Figure 7.3). The stages considered are the agricultural production, the distribution, the retail and the packaging production, as is described below.

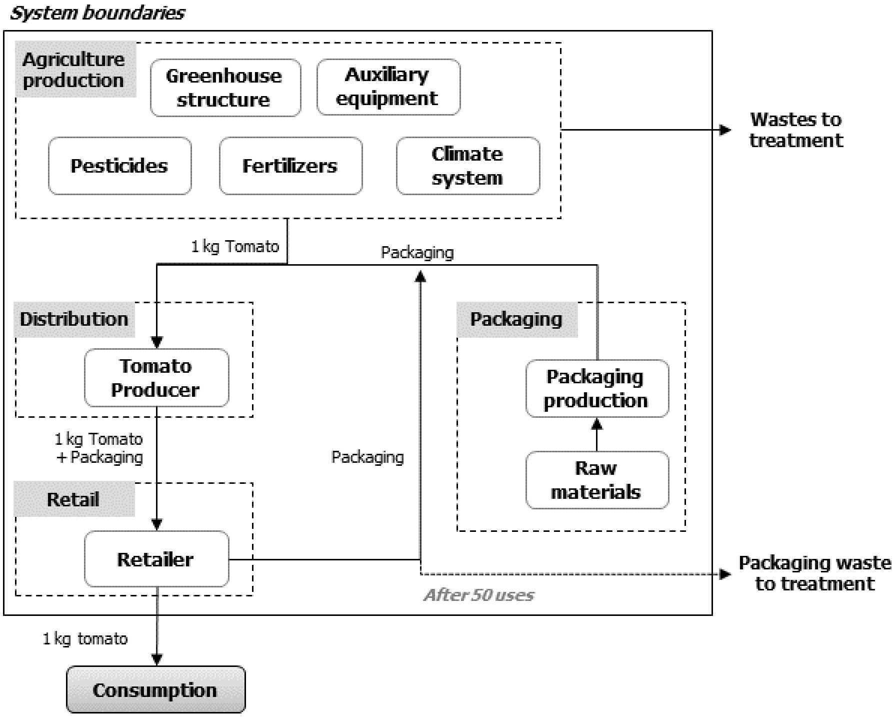


***Figure 7.3.*** *System description and boundaries for Scenario RTG (Rooftop Greenhouse) in Barcelona, as production and consumption site.*

*Agriculture production.* In the climatic context of Barcelona, the crop productivity is 15 kg·m$^{-2}$ per year according to Antón et al. (2005). The LCI data for this stage is obtained from the FP7 EU EUPHOROS project (Montero et al. 2011) and Torrellas et al. (2012). These works structured the LCA of the tomato production in five main subsystems (Figure 7.3), as explained above.

*Distribution stage.* Although no studies were developed about the retail of RTG products, several business models can be developed through RTG systems, even self-sufficiency crops. For this study, a small scale business was considered (neighbourhood scale). In this context, the implementation of RTG systems in Barcelona represents a tomato production system with less transport requirements and without product losses. Scenario RTG considers a system without transportation and without loss of product (Figure 7.3).

*Retail stage.* The retail stage is also developed in the city and the product is expected to be sold some hours after its recollection. In this sense, no product loss is considered during this stage due to the freshness of the product, which avoids damaging preservation techniques (such as freezing or ionizing radiation) (Edwards-Jones et al. 2008) (Figure 7.3).

*Packaging production.* Plastic tray (HDPE) is considered as packaging used for produced tomato to retail, as it can be used as a reusable packaging for food transport purposes, not as cardboard or wooden packaging (European Comission 2004). The packaging weights 900 gr., due to the reinforcement for multi-usage, and the lifetime considered is of 50 uses (ITENE and UPV 2008) (Figure 7.3).

***Table 7.2.*** *Life Cycle Inventory data for Scenario CLS and Scenario RTG, by stages, elements and flows. All units refer to the functional unit (1kg of tomato delivered to customer).*

| LCA phase | Element | Data per functional unit | Source |
|---|---|---|---|
| **Scenario CLS** | | | |
| *Inputs* | | | |
| Agriculture production | Product | 1.166 kg produced tomato | Montero et al. (2011)<br>Torrellas et al. (2012) |
| Distribution | Transport: | | |
| | To warehouse | 4.5-5t truck: 20 km | Cajamar (*pers. comm.*) |
| | To distribution centre | 40-45t refrigerated lorry 830 km | GavaGrup manager, (*pers. comm.*) |
| | To retail | 4.5-5t truck: 20 km | Retail survey data |
| | Electricity consumption | $0.743 \cdot 10^{-3}$ kWh | MercaBarna manager (*pers. comm.*) |
| Packaging | Plastic tray | 100 g HDPE | Retail survey data |
| *Outputs* | | | |
| Distribution | Dehydratation during transport | 66 g water vapour | GavaGrup manager (*pers. comm.*) |
| Retail | Organic waste to compost | 0.10 kg damaged tomato | Retail survey data |
| Packaging | Plastic tray | 100 g HDPE | Retail survey data |
| **Scenario RTG** | | | |
| *Inputs* | | | |
| Agriculture production | Product | 1 kg produced tomato | Montero et al. (2011)<br>Torrellas et al. (2012) |
| Packaging | Multi-way plastic tray | 3 g HDPE (50 uses) | Retail survey data |
| *Outputs* | | | |
| Packaging | Multi-way plastic tray | 3 g HDPE (50 uses) | Retail survey data |

## 7.3. Results and discussion

### *7.3.1. Environmental impact assessment*

The stages considered in the life cycle of 1 kg of tomato to consumption have different contributions to total environmental impact in the scenarios studied (Figure 7.4). In the current scenario (CLS), packaging production and agriculture production were the most contributing stages. On the one hand, packaging production was the main contributor to ADP (63.7%), AP (57.9%), GWP (44.9%) and ODP (61.0%); where the injection moulding for the packaging production was the most contributing stage, except for ADP and GWP, showing the importance of electricity consumption and solvent use. On the other hand, agriculture production was the first burden for EP (64.3%), due to fertilizers, and HTP (58.7%), and the second one for the other categories analysed (28 – 42%). The distribution stage made contributions with percentages between 3.8% and 10.2%. The transport from the warehouse (Almeria) to the distribution centre (Barcelona) was the first burden for all of the categories in this stage. Finally, the retail stage was considered relevant as contributions of 1.3 to 16.8%, with EP being the biggest contributor due to the composting of damaged product during this stage.

For the RTG Scenario, there were no motorized transports in the distribution stage assuming that a local production system was used, as well as there was no damaged product that needed to be composted in the retail stage due to the freshness of the product. So, packaging and agriculture production were the only contributors to environmental impact potentials. For RTG, agriculture production was the main burden for all the categories analysed with percentages higher than 92%.

Both scenarios showed GWP values within the range observed in published papers, not only for tomato production (0.14 – 0.81 kg $CO_2 \cdot kg^{-1}$) (Antón et al. 2005; Roy et al. 2008), but also for vegetables production and distribution (0.10 – 0.80 kg $CO_2 \cdot kg^{-1}$) (Milà i Canals et al. 2007). However, cardboard boxes showed lower GHG emissions (ITENE and UPV 2008; Roy et al. 2008) than plastic trays, most used packaging in the study area.

***Table 7.3.*** *Life Cycle Assessment (LCA) of Scenario CLS and Scenario RTG, RTG/CLS Ratio, savings per functional unit and per ha, by impact factor category and life cycle stage.*

| | **ADP** (g Sb eq) | **AP** (g $SO_2$ eq) | **EP** (g $PO_4^{3-}$ eq) | **GWP** (kg $CO_2$ eq) | **ODP** (mg CFC-11 eq) | **HTP** (kg 1,4-DB eq) | **CED** (MJ) |
|---|---|---|---|---|---|---|---|
| **Scenario CLS** | | | | | | | |
| Agriculture production | 1.93 | 1.21 | 0.57 | 0.30 | 0.027 | 0.10 | 4.66 |
| Packaging | 4.40 | 1.50 | 0.11 | 0.32 | 0.062 | 0.05 | 10.5 |
| Distribution | 0.44 | 0.29 | 0.006 | 0.06 | 0.010 | 0.007 | 0.90 |
| Retail | 0.14 | 0.14 | 0.15 | 0.03 | 0.002 | 0.017 | 0.20 |
| **TOTAL** | **6.91** | **3.14** | **0.88** | **0.70** | **0.102** | **0.17** | **16.3** |
| **Scenario RTG** | | | | | | | |
| Agriculture production | 1.66 | 1.04 | 0.49 | 0.25 | 0.023 | 0.087 | 4.00 |
| Packaging | 0.13 | 0.0045 | 0.0003 | 0.01 | 0.002 | 0.002 | 0.31 |
| **TOTAL** | **1.79** | **1.08** | **0.49** | **0.26** | **0.025** | **0.089** | **4.31** |
| Savings per FU | 5.12 | 2.06 | 0.39 | 0.44 | 0.077 | 0.086 | 11.9 |
| Savings per ha | 768,000 | 308,000 | 58,700 | 66,100 | 116 | 12,800 | 1,790,000 |
| Savings (%) | 74.1 | 65.5 | 44.4 | 62.6 | 75.5 | 48.8 | 73.5 |
| RTG/CLS ratio | 0.26 | 0.34 | 0.56 | 0.37 | 0.25 | 0.51 | 0.27 |

### *7.3.2. Cumulative Energy Demand (CED)*

The CED indicator showed that RTG systems could represent savings of 73.5% of the energy consumed in the current supply chain (Table 2). For the scenario CLS, the main contributor was the packaging production (64.5%), as the HDPE is made from crude oil. The agriculture production represented 28.7% of CED, while the other stages made contributions lower than 7%. On the other hand, for the scenario RTG, the main contributor was the agriculture production (92.7%), as the HDPE packaging had a lifetime of 50 uses and there was no fuel consumption for transportation. Therefore, an agriculture products supply model without transport requirements and with multi-way packaging systems could represent a high decrease in the energy consumption (Table 7.2).

Moreover, when CED values are related with the energy content of tomatoes, which is 190 kcal per kg (FAO 1995), this analysis showed that the CLS system needs to consume 20,000 times more calories than the energy content of 1kg of tomato while this ratio is of 5,400 for the RTG system. Jones (2002) showed a similar ratio of energy consumption for regional and home-grown produce.

### *7.3.3. Scenarios comparison*

Finally, a comparative analysis within the two scenarios showed that an RTG system implemented in Barcelona represented a reduction of 44.4 – 75.5% per kg in the different impact categories analysed. Main reductions, ODP (75.5%) and ADP (74.1%), were related to the change from a one-way packaging option to a multi-way one; while the least reduction, EP (44.4%), was associated to the agriculture production. In absolute values, a change from the current situation to RTG systems in Barcelona could represent a savings of 441 g of $CO_2$ eq. and 12 MJ of energy consumed per kg of tomato (Table 7.2).

These savings were related to the change from a linear system to a closed one due to three main factors.

- Higher efficiency. First, a lower impact of the agriculture stage was seen as the quantity of tomato produced and consumed (1 kg) was the same in the RTG scenario, without loss of product during transportation and retail stages. This is in contrast to the CLS scenario where the tomato produced (1.166 kg) was higher than the consumed (1 kg). Moreover, there was a composting of the loss of product during the retail stage (0.10 kg) in scenario CLS. The reductions associated to this subsystem ranged 7.3 to 37%, in the different categories, apart from the 58.4% for EP and of 72 g of $CO_2$ eq. in GWP per kg of tomato. Therefore, although CLS system has a higher productivity rate, RTG showed a best effectiveness rate when the overall system is considered, as less product is damaged.
- No need for transport. Second, a RTG scenario with urban cultivation of tomatoes does not require any motorized transport, as production and consumption take place in the same neighbourhood. This represented a reduction from 7.6 to 15.6%, in the different categories, and a saving of 62.3 g of $CO_2$ eq. in GWP per kg of tomato.
- Reusable packaging. Finally, the change to use a multi-way packaging option in a more controlled distribution system and with a higher lifetime (50 uses) resulted in a large reduction in the environmental profile. This represented the main contributor to the reductions, with a savings of 55.4 to 85.2% in the different categories, apart from EP (25.9%), and a decrease of 306 g of $CO_2$ eq. in GWP per kg of tomato.

For GWP, savings are substantial higher than previous works on regional and local, as transport (avoided in RTG systems) is one of the main contributors to GHG emissions. Weber and Matthews (2008) indicated that the savings of buying locally were around 5% in average for the American consumers. A Swedish study quantified the reduction in 30% assuming the local production of 13 basic food products (Sunnerstedt 1994). However, no previous studies characterised and quantified the distribution and retail for urban agriculture systems (such as RTG) and direct comparisons can produce wrong conclusions as a local product is understood as both a vegetable grown 50 km away and, merely, a national product (Edwards-Jones et al. 2008).

### 7.3.4. Reusable packaging option for Scenario CLS

As packaging was identified as the main contributor to the environmental impact reduction, a reusable packaging scenario was designed for the current system (CLS-Reusable scenario). A multi-way plastic tray (HDPE) of 900 gr. of weight was considered. 20 uses were assigned to the packaging (ITENE and UPV 2008), being less uses than the RTG system for two reasons. On the one hand, the packaging is more controlled in a RTG system, where is used in a smaller scale (neighbourhood, city) than in the CLS system (region, country). On the other hand, packaging is less damaged in a RTG system as there are no transportation requirements. Moreover, the packaging need to be returned to the origin, therefore the return trip from the distribution centre (MercaBarna) to the producer (Almeria) is included. According to the results, the CLS-Reusable scenario showed reductions from 10.9 to 58.9% of the environmental impact and savings of 59.6% of the energy consumed. However, RTG system had a better environmental profile for all the categories analysed.

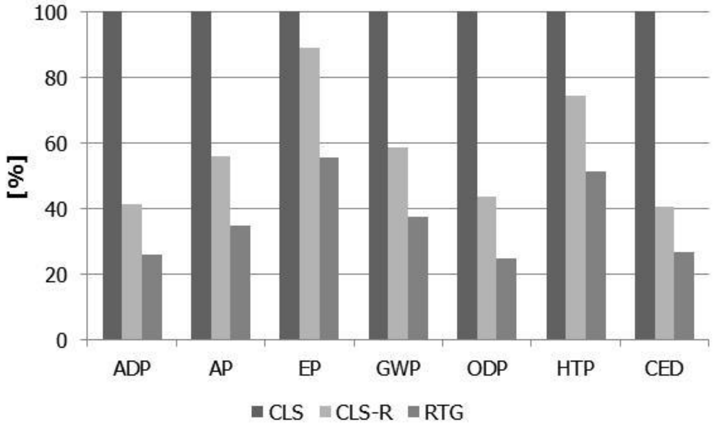


***Figure 7.4***. *Scenarios comparison: Current Linear System (CLS), Current Linear System with a reusable packaging option (CLS-R) and Rooftop Greenhouse system (RTG).*

### 7.3.5. Short-term implementation analysis: Urban scale impact

A number of studies identified 95ha as potential farming roofs in private and public buildings of Barcelona (BCN Ecologia 2010). Additionally, the municipality of Barcelona has a logistics area of 41 ha (Zona Franca), where RTG systems could be implemented. Therefore, the environmental impact per ha was calculated. The total environmental impact potential of 150,000 kg of tomatoes from Almeria that could be produced in 1 ha in Barcelona through RTG systems could represent a saving of 66.1 tonnes of $CO_2$ eq. and around 1,800 GJ of energy consumed (Table 2).

Moreover, the land transformation from wood to agricultural areas is avoided as RTG systems are integrated in the city. In this sense, the $CO_2$ fixation of woods might be considered in the analysis. According to Gracia et al. (2010), the average $CO_2$ fixation of Catalan woods is 4.93 t $CO_2$ per hectare and year. Therefore, the total savings of $CO_2$ emissions associated to the implementation of RTG systems in Barcelona are 71 tonnes per hectare. Thus, RTG systems demonstrate great opportunities for the design of low carbon cities. Apart from this, agrourban systems could use the current logistics infrastructure (streets, motorways) whereas new agriculture areas need to build up the rural paths for this purpose.

### *7.3.5. Economical, business models and building type approaches*

As first scientific approaches pointed out (Ecoponics project 2012; Cerón-Palma et al. 2012), RTG systems could have both positive and negative economic impacts. From the producer viewpoint, local production without a supply chain means a higher income as additional costs are avoided (Cerón-Palma et al. 2012). However, RTGs will have to be smaller than present commercial greenhouses on rural sites when implemented in cities, and this will inevitably mean increased production costs (Van der Meulen et al. 2009).

Nevertheless, higher prices can be obtained thanks to the greater freshness and improved nutritional value of the product, which would be fortified and already mature. In general, consumers will have safer and higher quality products (Ecoponics project 2012). Moreover, RTG systems would offer benefits (environmental and economic) for the building, such as energy saving due to a higher thermal isolation (≈40%) (Cerón-Palma et al. 2011; Cerón-Palma 2012), and for the city itself, providing new technology systems.

Secondly, cities will have a new urban model. RTG products would be produced and sold in the same city, while new specialized jobs and related-business are created. However, a specific business model is not matched yet with RTG systems. Instead of this, several business possibilities are identified: self-sufficiency, specialized urban enterprises (groceries), small markets, large retailers or new large enterprises. Furthermore, RTG systems can be used not only for monoculture crops but also for polyculture ones. Even so, the type of crop can be used for several business model and no unique scenarios can be defined.

Finally, RTG implementation can be done in different ways that entailed contrary economical costs. On the one hand, existing buildings can integrate RTG through a rehabilitation process or with the construction of structure reinforcements (due to higher rooftop's weight), involving a high investment. On the other hand, new buildings can integrate RTG systems and even consider the greenhouse-building flows in the design, which bring economic benefits due to savings of energy, water and production inputs consumption.

## 7.4. Conclusions

The implementation of RTG systems to cultivate tomato in the city of Barcelona could represent a reduction per kg of 44.4 – 75.5% in the different impact categories analysed. For global warming potential (GWP), tomato production in RTGs in Barcelona could represent savings of 441 g of $CO_2$ eq. and 12 MJ of energy consumed per kg.

The environmental benefits related to the change from a linear system to a closed one were tested and quantified. Main reductions were related to the change to use a multi-way packaging option representing from 55.4 to 85.2% of the reductions in the different categories, except for EP (25.9%), and a decrease of 306 g of $CO_2$ eq. in GWP per kg of tomato. The reductions of the transport requirements represented from 7.6 to 15.6% of the savings, in the different categories, and 62.3 g of $CO_2$ eq. in GWP per kg of tomato. Finally, from 7.3 to 37% of the reductions, in the different categories, were associated to the decrease of the loss of product in RTG systems, representing a reduction of 72 g of $CO_2$ eq. in GWP per kg of tomato.

A RTG scenario for Barcelona could represent a tomato production way without motorized transportation requirements. Main reductions were observed in categories related to the change from a one-way packaging option to a multi-way one (ODP (75.5%) and ADP (74.1%)). The Cumulative Energy Demand (CED) was calculated per energy content per kg of tomato. The RTG system showed energy savings of 73.5% which is related to the change to a multi-way packaging option, the reduction of the lost product and the elimination of the transport requirements.

Finally, a short-term implementation analysis was conducted as some studies have identified a potential for a farming roof area in Barcelona of 95 ha. The analysis showed that the production per ha could be 150,000 kg of tomatoes, saving per ha 66.1 tonnes of $CO_2$ eq. in GWP. Moreover, the land transformation from wood to agriculture crops avoided could total the savings of $CO_2$ emissions in 71.03 tonnes per ha. Considering that RTG could increase the productivity assumed in this study, RTG may become a strategic action in the design of low carbon cities. RTG systems with interconnection to the building could utilize the waste heat of the building as a heat input without energy requirements. In Barcelona, this system could produce throughout the entire year, potentially achieving productivity rates of 56.5 $kg \cdot m^{-2}$, like in the Netherlands (Montero et al. 2011). According to this, the production per ha could be 565,000 kg of tomatoes with a reduction of 249 tonnes of $CO_2$ eq. in global warming potential.

Apart from the logistics point of view, there are several issues related to the interconnected RTG systems that must be analysed. Examples of this include the energy requirements reduction for buildings as the RTG could increase the thermal isolation and the waste heat of the greenhouse can be used as input for buildings for heating purposes.

# Part IV

## Assessment of community and private rooftop farming

# Chapter 8

## Environmental and economic assessment of multiple cultivation techniques and crops in open-air community rooftop farming in Bologna (Italy)

Picture: *Lettuce production with floating technique (Bologna, Italy)*

*(©Esther Sanyé-Mengual)*

# Chapter 8

This chapter is based on the journal paper:

Sanyé-Mengual E, Orsini F, Oliver-Solà J, Rieradevall J, Montero JI, Gianquinto G (2015) Environmental and economic assessment of multiple cultivation techniques and crops in open-air community rooftop farming in Bologna (Italy). *Agronomy for sustainable development* (under review)

## Abstract

Urban rooftop farming (URF) is sprouting around cities thereby integrating agriculture in available urban spaces and enhancing local food production. Besides, different crops and cultivation systems can be used in URF. Quantitative environmental and economic information of these systems may support the design of future URF projects.

Life Cycle Assessment and Life Cycle Costing were used to quantify the environmental burdens and economic costs of an open-air community rooftop garden. For leafy vegetables (lettuce), three cultivation types were compared: Nutrient Film Technique (NFT), floating hydroponic and soil cultivation. Five different fruit vegetables (tomato, chilli pepper, eggplant, melon, watermelon) were grown in soil-less production. Experimental trials were realized between 2012 and 2014 in the rooftop garden of a public housing building in Bologna (Italy).

For leafy vegetables, most environmentally-friendly options were the floating technique in summer crops (65-85% lower) and soil production in winter (85-95% lower). In soil production, eggplants and tomatoes were the fruit vegetables that showed best environmental performances (≈74 g $CO_2 \cdot kg^{-1}$). From the economic point of view, floating production was 25% cheaper in summer and soil production was 65% cheaper than NFT production of lettuce, while substrate production of eggplants resulted in the cheapest crop (0.13 $€ \cdot kg^{-1}$). We here demonstrate that URF production is an environmentally-friendly option for further develop urban local production. We recommend that community URF designs include re-used elements and promote horticultural knowledge to improve their sustainability performance.

Keywords: urban agriculture; local food; building-integrated agriculture; rooftop farming; life cycle assessment; agronomy; hydroponics

## 8.1. Introduction

Urban Rooftop Farming (URF) is sprouting around cities driven by the growing interest in urban agriculture (Mok et al. 2013). URF is growing in popularity in such a way that urban planning policy has started to include it, such as in New York City. Rooftops have become a new resource thereby providing spaces for food cultivation in highly populated cities (Cerón-Palma et al. 2012; Specht et al. 2014; Thomaier et al. 2015). Among URF types, open rooftop farming is the most common (Thomaier et al. 2015) in contrast to more complex systems, such as rooftop greenhouses, which need a higher economic investment, or indoor farming, linked to a large energy demand.

Open-air rooftop farming experiences are found worldwide and range from educational to commercial projects. “Food from the sky” is a community food project that takes advantage of the empty rooftop of a supermarket in North London (United Kingdom) with the aim of increasing the community food security. In the Trent University (Toronto, Canada), an educational rooftop garden is managed by students to produce food for the local campus restaurant. The rooftop gardens in various Fairmont Royal Hotels in Canada supply the kitchen demand with own-cultivated herbs, tomatoes, peas, beans and berries in beds and pots. The Eagle Street rooftop farm and the Brooklyn Grange are the most well-known rooftop farms of New York (USA), which combine local food production with education and social programs.

Research on these forms of urban agriculture has mainly focused on theoretical and agronomic aspects. Thomaier et al. (2014) reviewed current URF projects and discussed their contribution to a sustainable urban agriculture. Cerón-Palma et al. (2012) and Specht et al. (2014) provided a compilation of barriers and opportunities of URF based on focus group discussions and available literature, respectively. Whittinghill et al. (2013) and Orsini et al. (2014) have performed agronomic studies of rooftop gardens to account for their productivity and their variability (e.g., different cultivation systems, seasonality) in Michigan (United States) and Bologna (Italy), respectively.

Notwithstanding the sustainable image of URF, only a few studies have focused on the quantification of their environmental, economic and social impacts. Astee and Kishnani (2010) analyzed the potential domestic vegetable production of rooftop farming in Singapore and the resulting $CO_2$ savings by reduced food imports. In the same line, Sanyé-Mengual et al. (2015a) evaluated the potential RTG implementation in industrial parks in Barcelona through a GIS-LCA guide, which includes a self-sufficiency and environmental assessment of local production. Sanyé-Mengual et al. (2013) quantified the environmental benefits of the local supply-chain of tomatoes produced in rooftop greenhouses (RTGs) in Barcelona (Spain) and contrasted with the conventional supply-chain of tomatoes from Almeria (Spain). Sanyé-Mengual et al. (2015b) accounted for the environmental burdens of the structure of an RTG and compared it to a conventional greenhouse, since more resources are consumed for reinforcing RTGs to meet legal requirements of buildings’ technical codes. However, the environmental and economic impacts of food production in open-air URF systems have not yet been studied. Furthermore, community URF experiences differ from other commercial systems (e.g., RTGs) as they provide further social services (e.g., social inclusion), are managed by amateurs and are usually low-cost designs.

Besides, multiple cultivation systems can be used in URF (FAO, 2013). Current projects involve from sophisticated growing systems (e.g., high-tech hydroponics) to soil-based crops cultivated in recycled containers (e.g. pallet cultivation). Among them, soil-based is the most commonly used technique (Thomaier et al. 2015). Even more, some rooftop farming experiences combine agriculture production with livestock, such as “The FARM:shop” in London (United Kingdom) which provides vegetables, fish and chicken products through an integrated rooftop-aquaponic system (Local action on Food 2012). Some studies have dealt with the efficiency of different cultivation techniques from an agronomic perspective. Pennisi (2014) compared the crop yield of producing lettuce in rooftop farming through NFT (Nutrient Film Technique), floating and substrate (i.e., mix of perlite, coconut fibre and clay) systems. At the city level, Grewal and Grewal (2012) quantified the potential production of urban agriculture, differentiating within cultivation scenarios, from conventional to hydroponic production, thereby highlighting the different efficiency and food supply capacity of them. In this sense, the quantification of the environmental burdens and economic costs of different cultivation systems for open-air farming may support the design decision-making process.

The general aim of the paper is to assess urban rooftop farming from an environmental and economic point of view. The objectives of the study are to quantify both the environmental impacts and economic costs of a real case study by applying the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methods. Specific objectives are, first, comparing three different cultivation techniques (NFT, floating, soil) for leafy vegetables production (lettuce); second, accounting for the burdens of soil production of multiple fruit vegetables (tomato, melon, watermelon, chilli pepper and eggplant); and, finally, assessing the sensitivity of the results to the availability of re-used materials and the use intensity of the rooftop garden. A community rooftop farming in the city of Bologna is analyzed for this purpose.

## 8.2. Material and methods

The paper analyses the outputs of experimental crops performed in Bologna (Italy) by following the LCA (ISO 2006a) and the LCC (ISO 2008) methods for accounting for the environmental burdens and the economic cost of the systems.

### *8.2.1. Experimental crops*

Experimental trials were performed from April 2012 to January 2014 in the rooftop of a public housing building in the city of Bologna (Italy). Bologna is a representative case study of Mediterranean cities, where climatic conditions are favourable for year-round open-air rooftop farming practices. The experimental crops were performed in a community garden implemented on the 250 m$^2$ terrace of the 10th floor of the building. Three different cultivation systems were used in the trials: modified NFT, floating and soil (illustrated in Figure 8.1). The modified NFT (Figure 8.1a) was done on re-used PVC pipes, where leafy vegetables were placed in net pots to be in contact with the nutrient solution, which was recirculated and supported with additional irrigation. The floating system (Figure 8.1b) consisted of a wooden container (made of re-used pallets and waterproofed with a plastic film), filled with the nutrient solution that was oxygenated with an aerator, where plants were grown on net-pots placed on a floating polystyrene board. Soil production (Figure 8.1c) was also done on wooden containers where plants were grown on commercial soil with compost and fertilizers. Tap water was used for irrigation in all the systems since rainwater harvesting (RWH) system were not considered in the design. Trials were performed for six crops including leafy and fruit vegetables: lettuce (*Lactuca sativa* L.), tomato (*Solanum lycopersicum* L.), melon (*Cucumis melo* L.), watermelon (*Citrollus lanatus* Thumb.), chilli pepper (*Capsicum annuum* L.) and eggplant (*Solanum melongena* L.) (Figure 8.1). Leafy vegetables were cultivated in NFT, floating and soil, while fruit vegetables were only grown in soil. Crop cycles are indicated in Figure 8.1 as Days-After-Transplanting (DAT) values. Other vegetables although not included in this analysis, were grown year-round in the garden. In particular, chicory and black cabbage were initially considered for assessing leafy vegetables production although they were finally excluded due to low crop yield values.

### *8.2.2. Life Cycle Assessment*

This section describes the goal and scope, Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) steps followed in both LCA and LCC analysis.

#### (a) Goal and scope

Crop production is assessed from a cradle-to-farm gate approach by including the following life cycle stages: cultivation system (i.e., the life cycle impact of cultivation elements), auxiliary equipment (i.e., irrigation system), crop inputs (i.e., substrate, energy, water and fertilizers) and waste management. The analysis is performed for each individual crop (i.e., lettuce, tomato, melon, watermelon, chilli pepper and eggplant) and the functional unit is 1 kg of product.

#### (b) Life Cycle Inventory (LCI)

Table 8.1 compiles the life cycle inventory of the three cultivation systems under assessment: NFT, floating and soil systems. LCI data for the assessment is divided into cultivation system, auxiliary equipment, and crop inputs. Cost data is shown in terms of unitary costs and per year of use.

***Table 8.1.*** *LCI data for modified NFT, floating and soil, for 1 m$^2$ and a lifespan of 1 year. Crop inputs are defined per year, crop or day, depending on cultivation systems. Water and electricity consumption for irrigation is shown per day since crop cycles are different and water demand depends on crop.*

| | Element | Material | Unit | Cultivation systems | | | Unitary cost | |
|---|---|---|---|---|---|---|---|---|
| | | | | NFT | Floating | Soil | | |
| **Cultivation system** | Pallet | Wood | kg | - | 3.34 | 3.34 | 0 | €·kg$^{-1}$ |
| | Screws | Steel | kg | - | 0.007 | 0.007 | 23.8 | €·kg$^{-1}$ |
| | Angle iron | Iron | kg | - | 0.052 | 0.052 | 11.5 | €·kg$^{-1}$ |
| | Wood agent | Varnish | L | - | 0.02 | 0.02 | 0.81 | €·L$^{-1}$ |
| | Pipes | Polyvinylchloride (PVC) | kg | 1.62 | - | - | 0 | €·kg$^{-1}$ |
| | PS board | Polystyrene (PS) | kg | - | 0.27 | - | 0.096 | €·kg$^{-1}$ |
| | Construction | Electricity | kWh | - | 0.009 | 0.009 | 0.1539 | €·kWh$^{-1}$ |
| | Transport | Van, 3.5t | kgkm | 4.7 | 21.5 | 20.8 | 0.003 | €·kgkm$^{-1}$ |
| **Auxiliary equipment** | Sticks for support | Bamboo | kg | - | - | 0.18 | 0 | €·kg$^{-1}$ |
| | Net pot | PVC | g | 25 | 46 | - | 0.074 | €·g$^{-1}$ |
| | Water tank | PVC | g | 223.5 | - | - | 0.012 | €·g$^{-1}$ |
| | Irrigation tubes | Polyethylene (PE) | g | 56.6 | - | 12 | 0.004 | €·g$^{-1}$ |
| | Drippers | Polypropylene (PP) | g | 2.8 | - | 11.1 | 0.17 | €·g$^{-1}$ |
| | Microtubes | PVC | g | 2.3 | - | 3.6 | 0.04 | €·g$^{-1}$ |
| | Supporting stakes | PP | g | 6.8 | - | 2.7 | 0.03 | €·g$^{-1}$ |
| | Barbed connectors | PP | g | 2.3 | - | 0.9 | 0.15 | €·g$^{-1}$ |
| | Transport | Van, 3.5t | kgkm | 2.6 | 0.23 | 1.22 | 0.003 | €·kgkm$^{-1}$ |
| | Timer | - | - | 1/8.5 | - | 1/36 | 2.70 | € |
| | Aerator pump | - | - | - | 1/1.2 | - | 6.62 | € |
| | Recirculation pump | - | - | 1/8.5 | - | - | 3.47 | € |
| **Crop inputs** | Water | Tap water | L·d$^{-1}$ | - | - | 2.6-11.7 | 0.00153 | €·L$^{-1}$ |
| | Electricity | Timer/Pump | kWh·d$^{-1}$ | 0.0624 | 0.019 | 0.0033 | 0.1539 | €·kWh$^{-1}$ |
| | Fertilizers | Compost | g·y$^{-1}$ | - | - | 210 | 0 | €·g$^{-1}$ |
| | | NPK 15-5-20 | g·y$^{-1}$ | - | - | 30 | 0.001 | €·g$^{-1}$ |
| | Fertirrigation | Nutrient solution | L·d$^{-1}$ | 1.96-3.92 | 1.3-4 | - | 0.003 | €·L$^{-1}$ |
| | Substrate | Commercial soil | kg·y$^{-1}$ | - | - | 2.09 | 0.045 | €·kg$^{-1}$ |
| | | Perlite | kg·crop$^{-1}$ | 0.27 | 0.49 | - | 0.493 | €·kg$^{-1}$ |
| | | Coir | kg·crop$^{-1}$ | 0.27 | 0.49 | - | 0.453 | €·kg$^{-1}$ |
| | | Clay | kg·crop$^{-1}$ | 0.27 | 0.49 | - | 0.267 | €·kg$^{-1}$ |
| | Transport | Van, 3.5t | kgkm | 29.19 | 51.10 | 12.75 | 0.003 | €·kgkm$^{-1}$ |
| **Waste management** | Transport | Van, 3.5t | kgkm | 58.2 | 111.37 | 108.31 | 0.003 | €·kgkm$^{-1}$ |

*Cultivation systems and auxiliary equipment*

The cultivation systems included in the analysis are modified NFT in PVC pipes, floating in wood container and soil in wood container (Figure 8.1). Type and amount of materials are obtained from the experimental trials in Bologna and the designs detailed in Marchetti et al. (2012). Wood containers are made of re-used pallets while former PVC pipes are used in the NFT system. When materials are re-used, the environmental impacts of their extraction and manufacturing are excluded from the assessment as they belong to the former product. The auxiliary equipment includes all the elements related to the irrigation system required for each crop. Pumps and timer materials are excluded from the system boundaries due to the low repercussion per functional unit, based on a mass cut-off criterion. LCI data is compiled in Table 8.1. LCI background data for materials extraction, processing, transportation and electricity generation are obtained from ecoinvent 2.2. database (Swiss Center for Life Cycle Inventories 2010). Since the cultivation systems are used year-round for multiple crops, their impact is allocated for each crop product according to their crop cycle (indicated as Days-After-Transplanting values in Figure 8.1).

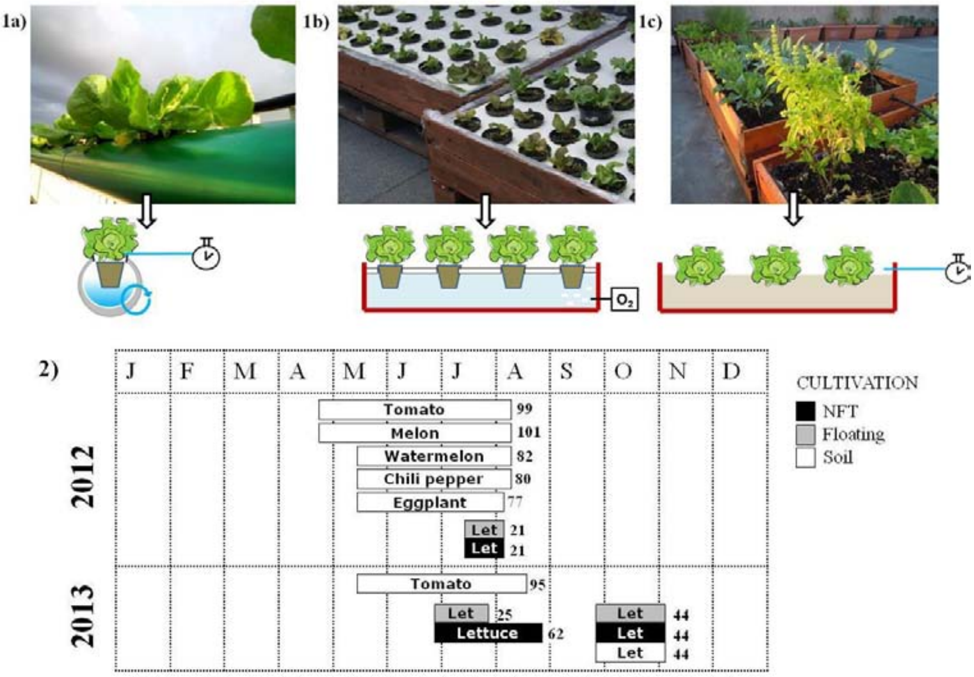


***Figure 8.1.*** *The experiment considered three different cultivation types for leafy vegetables: floating in wooden containers (1a), modified NFT in PVC pipes (1b) and soil in wooden containers (1c). Experiments were performed between 2012 and 2014 (2). The six crops followed different cycles: spring-summer, summer, autumn or autumn-winter (2).*

*Crop inputs*

Crop inputs depend on cultivation system and crop. First, water consumption is determined by cultivation system, crop, plant density and crop cycle. For soil cultivation, irrigation is of 11.7 L·m$^{-2}$·d$^{-1}$ for tomato and lettuce, 4.7 L·m$^{-2}$·d$^{-1}$ for eggplant, 7.2 L·m$^{-2}$·d$^{-1}$ for chilli pepper, 2.6 L·m$^{-2}$·d$^{-1}$ for melon and 3.7 L·m$^{-2}$·d$^{-1}$ for watermelon. For NFT, crops are irrigated with the nutrient solution through a recirculation system at a rate of 1.9 L·m$^{-2}$·d$^{-1}$ in autumn-winter cycles and of 3.9 $L \cdot m^{-2} \cdot d^{-1}$ in summer cycles. For floating cultivation, the container is filled with the nutrient solution and losses per evapotranspiration are replaced, resulting into a consumption of 1.3 $L \cdot m^{-2} \cdot d^{-1}$ in autumn-winter cycles and of 4 $L \cdot m^{-2} \cdot d^{-1}$ in summer cycles. Energy consumption includes the requirements for the irrigation timer, the recirculation pump (i.e., NFT) and the aerator (i.e., floating).

Fertilizers are supplied in a solid form in soil cultivation and as a nutrient solution in NFT and floating. For soil, 30 $g \cdot m^{-2} \cdot y^{-1}$ of N-P-K 15-5-20 with 2 $g \cdot m^{-2} \cdot y^{-1}$ of MgO and micronutrients are yearly supplied. For NFT and floating, the nutrient solution contains the following fertilizers: NPK (80 $mg \cdot L^{-1}$), $CaNO_3$ (30 $mg \cdot L^{-1}$) and $KNO_3$ (40 $mg \cdot L^{-1}$). Soil cultivation is done on potting soil, where compost is added to regenerate it and to complete fertilization at a rate of 210 $g \cdot m^{-2}$ of soil. Compost is made by the rooftop garden users by composting the biowaste from crops and their own organic waste. Plants in NFT and floating systems are placed on net pots with a mix of substrates: perlite (1/3), coconut fibre (1/3) and expanded clay (1/3). All crops are pesticide-free.

LCI data is obtained from the experimental trials, detailed in Orsini et al. (2014) and Marchetti (2012). LCI data for home composting of green biowaste is obtained from Colón et al. (2010). Background data for the LCI is completed from the ecoinvent 2.2. database (Swiss Center for Life Cycle Inventories 2010) and the LCA Food database (Nielsen et al. 2003).

*Waste management*

Waste management includes only the management of the elements of the cultivation materials at their end of life, since biomass is reintroduced in the crop cycle through composting. Cultivation materials (i.e., from cultivation system and auxiliary equipment) are 100% recyclable. As a result, their treatment is excluded from the analysis and only their transportation is considered (recycling plants are located 30 km away from the site).

*Cost data*

Costs of the different materials and elements of the cultivation systems and auxiliary equipment are obtained from suppliers, as well as for substrate and fertilizers. Tap water cost is 0.00153 $€ \cdot L^{-1}$, according to Bologna's supplier (Gruppo Hera). Electricity cost is 0.1539 $€ \cdot kWh^{-1}$ (EUROSTAT 2014). Transportation cost is 0.003 $€ \cdot kgkm^{-1}$, according to the transport type, consumption rate and current fuel prices. Material costs of re-used elements are considered as 0, although the related transportation and construction requirements are accounted for.

### (c) Sensitivity assessment

Two variables are assessed as sensitivity parameters: the availability of re-used elements and the use intensity of the rooftop garden. First, although the current design is made of re-used materials, they can be also made with new pallets and pipes (e.g., lack of re-used pallets sources), particularly when re-used elements are unavailable. Thus, a "Raw materials scenario" shows the potential increase in the resources consumption, considering that cultivation systems are made of new elements (i.e., raw materials) and multiple crops are done during the entire year (i.e., environmental impacts and costs of the cultivation system are allocated to the different crop periods).

Second, community and private gardens can be used seasonally, leading to a low use intensity (e.g., only summer crops), or can be year-round thereby combining autumn-winter and spring-summer crop cycles. A "Low use intensity scenario" assumes that only one crop is done during the entire year and, therefore, the environmental impacts and costs of the cultivation system of the entire year are allocated to one crop.

### (d) Life Cycle Impact Assessment (LCIA)

The environmental impact assessment is performed by applying the LCIA stage. The SimaPro 7.3.3 software (PRé Consultants 2011) is used to conduct the LCIA, which follows classification and characterisation steps determined as mandatory by the ISO 14044 regulation (ISO 2006a). The LCIA is carried out at the midpoint level, and methods applied are the ReCiPe (Goedkoop et al. 2009) and cumulative energy demand (CED) (Hischier et al. 2010). With respect to the ReCiPe, the hierarchical time perspective is considered, as recommended in the ILCD Handbook (EC-JRC 2010). The environmental indicators include the global warming (GW, kg $CO_2$ eq), the water depletion (WD, $m^3$) and the cumulative energy demand (CED, MJ). Besides, the human toxicity potential (HT, kg 1.4-DB eq.) is used to evaluate potential effects on human health. The LCC assessment considers the cost of the systems and results are shown through the total cost (TC, €) indicator.

## 8.3. Results and discussion

The environmental impacts and economic costs of crop production in open-air rooftop farming are shown and discussed in this section. First, the three cultivation techniques under assessment (soil, NFT, floating) are compared for the production of leafy vegetables. Second, the environmental performance and costs of soil production for multiple vegetables are discussed. Finally, the sensitivity of the results to the availability of re-used materials and the use intensity of the garden is assessed.

Table 8.2 compiles the environmental and economic results for the production of fruit and leafy vegetables in the rooftop garden. Soil production of eggplant and tomato obtained the lowest environmental impact in global warming (0.073 kg $CO_2eq\cdot kg^{-1}$), human toxicity (0.027 kg 1-4DBeq$\cdot kg^{-1}$) and energy consumption (1.20 MJ$\cdot kg^{-1}$), while eggplant was the cheapest crop (0.17 €$\cdot kg^{-1}$). Lettuce production in floating technique was the most water efficient production (<0.04 $m^3\cdot kg^{-1}$). On the contrary, lettuce production in NFT was the most expensive (1.47 €$\cdot kg^{-1}$, on average) and the most impacting crop in global warming (3.78 kg $CO_2eq\cdot kg^{-1}$, on average), human toxicity (0.84 kg 1-4DBeq$\cdot kg^{-1}$, on average) and energy consumption (57.1 MJ$\cdot kg^{-1}$, on average), because of the large energy consumption of the recirculation pump and the low crop yield (1.3 $kg\cdot m^{-2}$, on average). Finally, lettuce production in soil consumed the largest amount of water (0.39 $m^3\cdot kg^{-1}$) since soil production is the least water efficient system and crop yield was low (1.5 $kg\cdot m^{-2}$). When correlating these results with the agronomic data, relation to crop yield and crop period were moderately significant ($R^2>0.6$). The lower the crop yield and the longer the crop period, the higher the environmental impacts and costs.

***Table 8.2.*** *Environmental and economic indicators for modified NFT, floating and soil production. Results correspond to the functional unit of 1 kg of product per crop period. Indicators are Global Warming (GW, kg $CO_2$ eq), Water depletion (WD, $m^3$), Cumulative Energy Demand (CED, MJ), Human Toxicity (HT, kg 1,4-DB eq.) and Total cost (TC, €).*

| | **GW [kg $CO_2$ eq,]** | **HT [kg 1-4DB eq,]** | **WD [$m^3$]** | **CED [MJ]** | **TC [€]** |
|---|---|---|---|---|---|
| NFT | | | | | |
| Lettuce-2012 | 2.51 | 0.542 | 0.0911 | 38.1 | 1.09 |
| Lettuce-2013(1) | 4.88 | 1.09 | 0.196 | 73.3 | 1.36 |
| Lettuce-2013(2) | 3.97 | 0.889 | 0.0855 | 60.5 | 1.95 |
| FLOATING | | | | | |
| Lettuce-2012 | 0.567 | 0.109 | 0.0395 | 9.37 | 0.67 |
| Lettuce-2013(1) | 1.19 | 0.234 | 0.0904 | 19.6 | 1.42 |
| Lettuce-2013(2) | 1.08 | 0.231 | 0.0393 | 18.6 | 1.29 |
| SOIL | | | | | |
| Chilli pepper | 0.174 | 0.06.10 | 0.158 | 2.80 | 0.35 |
| Eggplant | 0.0766 | 0.02.41 | 0.0501 | 1.21 | 0.13 |
| Lettuce-2013(2) | 0.323 | 0.123 | 0.389 | 5.15 | 0.74 |
| Melon | 0.194 | 0.0553 | 0.0788 | 3.05 | 0.28 |
| Tomato-2012 | 0.0753 | 0.0308 | 0.0980 | 1.26 | 0.18 |
| Tomato-2013 | 0.0679 | 0.0277 | 0.0881 | 1.14 | 0.16 |
| Watermelon | 0.133 | 0.0399 | 0.0719 | 2.09 | 0.21 |

From the economic perspective, prices ranged between 0.13 and 1.95 €·$kg^{-1}$ and irrigation was the most contributing stage. Overall production costs of some crops (e.g., NFT and floating lettuce production) resulted larger than current market prices because of two main issues. First, given the importance of water consumption, urban gardeners pay a higher value for water since drinkable water is more expensive than water in rural agrarian areas. Second, one may consider that community rooftop farming provides further services than the food production itself. Thus, social services such as hobby, community building or education may be included in the cost-benefit assessment by accounting for the economic value of these positive externalities.

### *8.3.1. Comparing cultivation techniques for leafy vegetables*

Figure 8.2 compares the environmental impacts and economic costs of lettuce production in NFT, floating and soil. Results depended on the season. In summer cycles, floating production of lettuce showed the lowest environmental burdens and economic costs. In winter cycles, soil production was the most environmentally-friendly and cheapest option, although floating production was the most water-efficient one.

For lettuce production in summer, floating production had an environmental impact per kg around 75% lower and costs were 25% cheaper than NFT. Causes of this divergence are the lower crop yield in NFT (46% lower), the longer crop period (almost 2 times, on average), the electricity consumed by the recirculation pump and the higher water consumption in the NFT system.

For lettuce production in winter, soil was the more environmentally-friendly and cheaper option, apart from the water depletion indicator where the floating technique consumed the lowest amount per kg (0.04$m^3$·$kg^{-1}$). Electricity consumption for irrigation purposes was the lowest in soil production (i.e., timer), compared to the other systems where the use of electric devices is more intensive (i.e., recirculation pump, aerator). However, water consumption in soil production was 10 times larger because of a longer crop cycle, a lower crop yield (1 $kg \cdot m^{-2}$, the lowest of the three techniques) and larger irrigation requirements per kg of product. In particular, soil production of leafy vegetables became a water inefficient system, since the irrigation rate ($1.3 L \cdot day^{-1} \cdot plant^{-1}$) was the same as for some fruit vegetables (e.g., tomato). Thus, leafy vegetables were irrigated at a fruit vegetable rate although their water requirements are lower. This is caused by the simultaneous production of multiple vegetables, while in a monoculture design water requirements would be crop-specific.

As a result, NFT is the worst option from both an environmental and economic perspective. Furthermore, notwithstanding the feasibility of using NFT crops in Bologna area, the use of this technique in the Mediterranean climate is limited to moderate temperatures. Major temperature changes can be produced in warmer areas (south Mediterranean) due to the low volume of nutrient solution, leading to a higher risk of plant mortality (FAO 2013b).

For all the cultivation techniques, ‘crop inputs’ was the most contributing life cycle stage to the different environmental indicators (>85%). In NFT production, 70% of the environmental impact was associated with the electricity consumed during irrigation, in particular for the recirculation of the nutrient solution. In floating production, the irrigation (nutrient solution and electricity) was responsible for 60% of the impact. In soil production, water accounted for the 75% of the overall impact. Furthermore, auxiliary equipment related to the irrigation system (e.g., timer, pump) made this life cycle stage the second most expensive one. Thus, improvements in the design of cultivation systems for leafy vegetables may focus on the irrigation requirements and the associated elements.

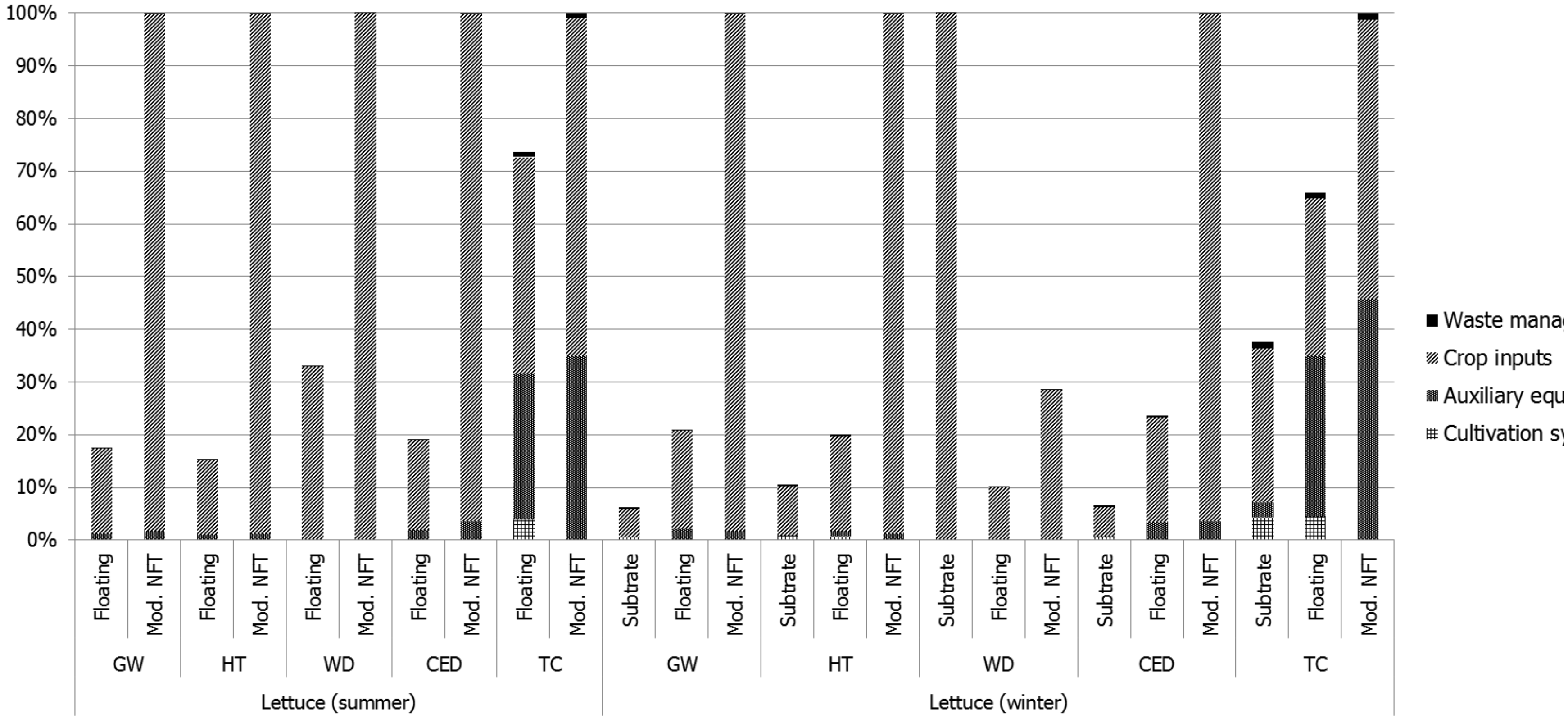


***Figure 8.2.*** *Environmental and economic burdens of soil, NFT and floating production for leafy vegetables: lettuce. The indicators used are Global Warming (GW, kg $CO_2$ eq), Water depletion (WD, $m^3$), Cumulative Energy Demand (CED, MJ), Human Toxicity (HT, kg 1,4-DB eq.) and Total cost (TC, €).*

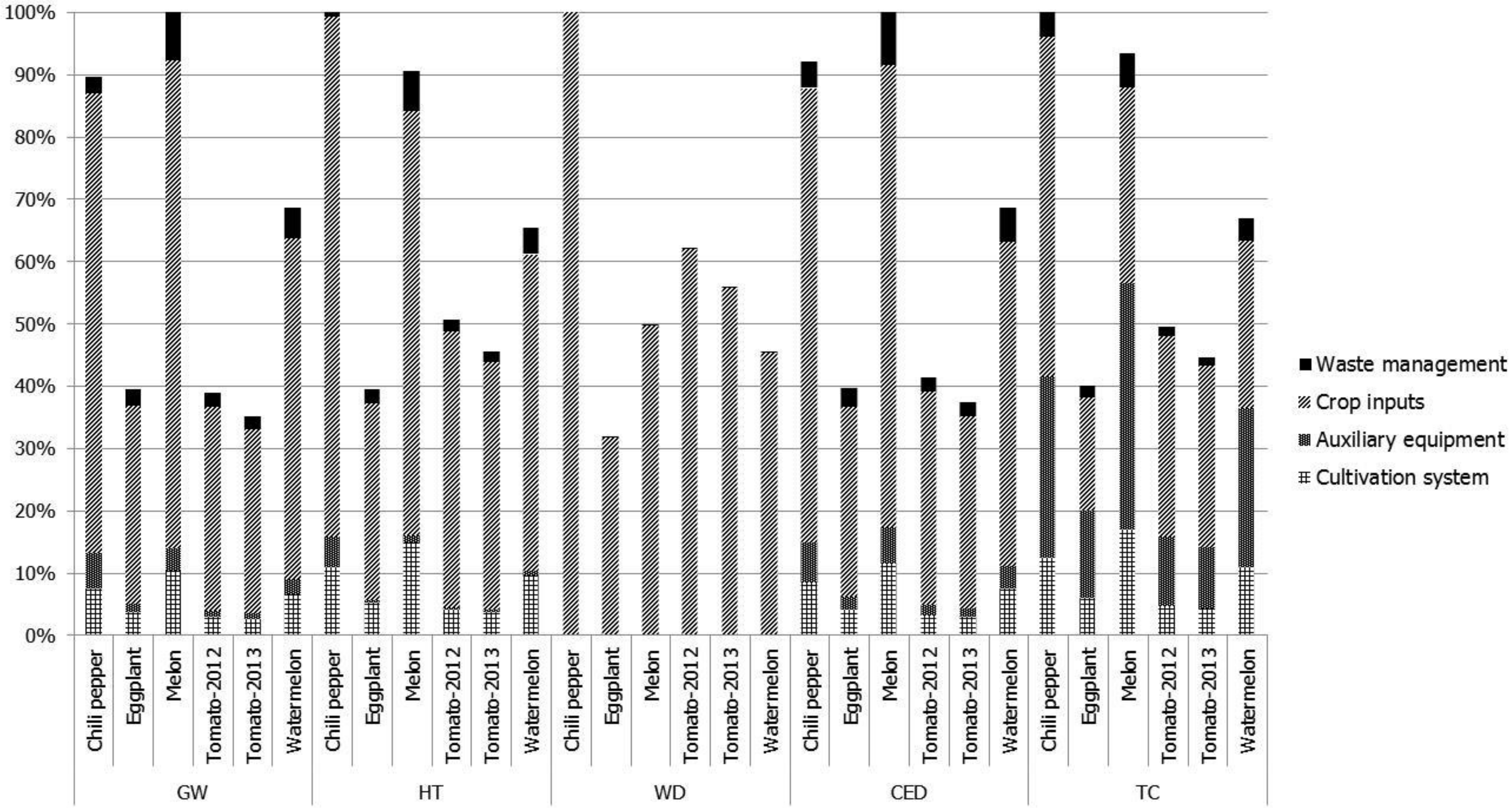


*Figure 8.3.* *Environmental and economic burdens of soil production for leafy and fruit vegetables. The indicators used are Global Warming (GW, kg $CO_2$ eq), Water depletion (WD, $m^3$), Cumulative Energy Demand (CED, MJ), Human Toxicity (HT, kg 1,4-DB eq.) and Total cost (TC, €).*

### *8.3.2. Soil production of fruit vegetables*

Figure 8.3 displays the environmental impact and economic cost of soil production of fruit vegetables. These crops had a global warming impact ranging from 68 to 194 g of $CO_2$ eq., a human toxicity impact between 0.02 and 0.7 kg 1-4DB eq, a water depletion between 50 to 158 L, and an energy consumption between 1.14 a 3.05 MJ. Total costs per kg varied from 0.17€ to 0.44€, being the crop inputs the major cost (52%, on average) (Table 8.2). The life cycle stage that contributed the most to the environmental indicators turned out to be the irrigation (≈ 70%), particularly in water depletion where it accounted for almost the 100%. Within the irrigation system, the consumption of tap water was the main contributor to the water depletion (≈ 52%) and economic cost (≈ 80%), while the electricity consumed by the pump and the timer was the main cause (45-65%) of the other environmental indicators.

Among fruit vegetables, the production of tomatoes and eggplants were the cheapest and most environmentally-friendly crops. This trend is related to the high yield of these crops (8.2 $kg \cdot m^{-2}$ for eggplant and 13-14 $kg \cdot m^{-2}$ for tomatoes), compared to the other crops with productivities lower than 5 $kg \cdot m^{-2}$. On the other hand, chilli pepper and melon were the crops that obtained the highest impact values, depending on the indicator (Table 8.2).

Since irrigation was the most contributing element, the use of rainwater harvesting systems may reduce the environmental impact. The substitution of the current tap water consumption with collected rainwater could reduce the global warming impact by between 12 and 60%, depending on the crop. When the amount of rainwater collected satisfies the whole crop water demand, water depletion could be avoided (i.e., become 0). Although there is available space in the rooftop garden for introducing rain-collecting systems, the main constrain is actually given by the weight load of these reservoirs, which were not considered when the building was designed. On the other hand, if rainwater would be stored at ground level, supplementary energy to pump it to the 10th floor may be considered in the environmental and economic balance. However, for newly implemented buildings with integrated rooftop gardens, these constrains may be easily overtaken.

### *8.3.3. Cultivation systems design: sensitivity assessment of availability of re-used materials and use intensity of the garden*

The sensitivity to the availability of re-used materials and the use intensity of the garden was analyzed. Primarily, environmental impacts and economic costs of crop production in cultivation systems built with new elements (i.e., new pallets and new PVC pipes) were compared with the case study (i.e., re-used pallets and pipes). The environmental impact of a "raw materials scenarios" was from 1.1 (NFT) to 1.8 (soil) folds higher than the reference scenario. The most sensitive indicator was the CED, which rose up to 3 times in soil production (data not shown).

The availability of re-usable elements in urban areas may be a limiting factor for the design of sustainable rooftop farming systems. In this case study, pallets and PVC pipes are the re-usable elements. First, pallets are growing in popularity due to their suitability for designing household elements, such as furniture, and garden elements. To date, the used pallets market is growing and availability seems guaranteed due to the worldwide use of these elements in the logistics sector. On the other hand, re-usable PVC pipes are less available for citizens, although the integration of these elements in a growing market of re-used elements may become way to manage the end-of-life of the current tap water distribution network. Moreover, PVC pipes have the lower global warming impact of the most common pipes used in urban water distribution networks (Sanjuan-Delmás et al. 2014).

Results of the year-round production systems (Table 8.2) were also compared to crop production in cultivation systems where only one crop is done per year (i.e., seasonal use). A "low use intensity scenario" showed an increase in the environmental impact of between 1.2 (NFT) and 2 (floating) folds (data not shown). Again, CED resulted to be the most sensitive indicator. Consistently, the impact associated with rooftop gardening can be highly affected by its use intensity. As a matter of fact, educational and training programs from public entities (e.g., municipality, associations and educational centres) are therein crucial in enabling citizens' knowledge on horticultural systems and their appropriate management. Skills on horticulture, crop production and crop planning may enhance the sustainability of community rooftop farming by leading to a year-round production (e.g., diversification of crops and crop cycles).

For lettuce (multiple crop cycles), the sensitivity to use intensity and availability of re-used materials was related to crop yield and crop period values. On NFT, the variation in the environmental impact of lettuce production was strictly related to the crop yield ($R^2 > 0.99$). The higher the crop yield, the lower the variation in the environmental indicators. On the contrary, the sensitivity to the availability of re-used elements for the design depended on the crop period ($R^2 \approx 0.8$). The shorter the crop period, the lower the increase in the environmental indicators when using new materials. The same trends were found for lettuce production in floating technique.

## 8.4. Conclusions

The paper accounted for the environmental impacts and economic costs of crop production in a community rooftop farming in Bologna, thereby contributing to the sustainability assessment of urban agriculture from a quantitative approach. The environmental impacts and economic costs of the crops strongly depended on cultivation technique, crop yield and crop period. Soil production of eggplants and tomatoes, which had the highest crop yields, showed the best environmental and economic performance, except for water consumption where lettuce production in floating technique was the most efficient option. For leafy vegetables, floating technique and soil production were the best options, depending on the indicator and season.

As a community-managed system, the home-made compost and pesticides-free production allowed decreasing the chemicals consumption in soil crops. Furthermore, the crop diversity of the community garden positively contributed to supply the food demand of the residents and use the garden year-round. Finally, the knowledge and training of rooftop garden users can affect the environmental and economic indicators, depending on their crop management efficiency and the final outputs of the rooftop farming.

Compared to other types of urban rooftop farming, the case study showed better environmental and economic performances than rooftop greenhouses. For instance, tomatoes produced in the open-air rooftop garden in Bologna had a global warming impact 3 times lower and economic cost 3.5 times lower than tomatoes produced in a Rooftop Greenhouse in Barcelona, from a cradle-to-farm gate approach (Sanyé-Mengual et al. 2015). Thus, rooftop gardens can become a key way to promote urban agriculture in residential areas, where the investment in high-tech infrastructures (e.g., greenhouses, aquaponics) is more unlikely. Even more, residents can obtain cheap and environmentally-friendly products that can boost the food security of urban areas (Orsini et al. 2014) and, in particular, can benefit certain marginal areas and stakeholders groups with little access to healthy food.

Notwithstanding the potential benefits of open-air rooftop farming, the design of the cultivation system and the crop planning are crucial points to optimize the environmental and economic performance of these systems. Rooftop farming design may focus on the potential local resources that can be used in the construction stage, particularly on those elements that can have a second life in the garden through re-use (e.g., pallets, pipes, wheels). Moreover, the design may include different type of cultivation systems. This is because fruit and leafy vegetables have different requirements. According to the results, we would recommend the use of soil techniques for fruit vegetables and winter cycles of leafy vegetables, while floating production would be interesting for summer crops of leafy vegetables. On the contrary, NFT would be the least recommended option. Regarding management, crop planning may focus on selecting the vegetables (e.g., combination of fruit vegetables with higher crop yield and leafy vegetables) and establishing crop periods to diversify the production during spring-summer and fall-winter cycles, thereby producing year-round and reducing the environmental impacts and economic costs of crops. Further research may focus on applying social indicators in URF future studies or integrate social services as positive externalities in the overall economic balance.

# Chapter 9

## Revisiting the environmental assessment of local food: Relevance of market data and seasonality.

### *A case study on rooftop home-grown food in Barcelona (Spain).*

Picture: *Gran Via rooftop garden (Barcelona, Spain)*
*(©Joan Rieradevall Pons)*

# Chapter 9

This chapter is based on the journal paper:

> Sanyé-Mengual E, Oliver-Solà J, Montero JI, Rieradevall J (2015) Revisiting the environmental assessment of local food: Relevance of market data and seasonality. A case study on rooftop home-grown food in Barcelona (Spain). *International Journal of Life Cycle Assessment* (submitted)

## Abstract

The growing interest in urban agriculture is also performed at the individual level by increasing the home-grown food sector and environmental data of these types of local food products might shed light on the sustainability potential of such experiences. For this purpose, this paper evaluates from an environmental perspective a pilot experience in a private rooftop garden in the city centre of Barcelona (Spain). Beyond accounting for the environmental burdens of food production, the system is also evaluated from a local production approach by quantifying the avoided food-miles for each product. Attention is paid to the relevance of integrating detailed and seasonal market data of imported conventional in the assessment. Home-grown products had similar environmental impacts than other rooftop systems. Even more, tomato production showed lower environmental burdens than conventional production. These results indicate that home-grown products might be a sustainable way of expanding local food systems in urban areas. Fruit (i.e., tomato) and root (i.e., beet) vegetables had a lower environmental impact than leafy vegetables and differences where larger when considering the nutritional value as functional unit. Detailed market data and seasonality were relevant in the assessment. In some cases, detailed market data accounted for avoided food-miles up to 12 times higher. The monthly food-miles varied up to 87%, highlighting the relevance of seasonality for some products.

**Keywords:** Urban agriculture, rooftop farming, home garden, life cycle assessment, local production

## 9.1. Introduction

The increasing urban population and consequent increasing food demand has raised the awareness of the urban food issue in terms of food security and environmental consciousness of the global food system (UNEP 2011; UNEP 2013; UN-Habitat 2013). In this context, urban agriculture (UA) is growing in developed countries to counter this problematic by enhancing new urban food systems to supply local food, address specific social gaps (e.g., food deserts, social inclusion) and provide further sustainability services to cities (e.g., biodiversity) (Wrigley et al. 2004; McClintock 2010; Cohen et al. 2012; Mok et al. 2013; Ackerman et al. 2014; Orsini et al. 2014; Lin et al. 2015). The expansion of UA has recently colonized urban buildings thereby taking advantage of unused spaces (Cerón-Palma et al. 2012; Specht et al. 2014; Thomaier et al. 2015). In particular, urban rooftop farming (URF) encompasses rooftop gardens, rooftop farms and rooftop greenhouses, such as Brooklyn Grange (New York, United States) or Lufa Farms (Montreal, Canada).

Beyond commercial and community UA projects, there is a proliferation of private home gardens. According to the literature, citizens cultivate their own food at home or in private gardens in order to access ecological products that they can trust (i.e., home-grown food ensures a chemical-free product), access products of a higher quality, have a space for leisure and hobby and reduce their daily food costs(Howe and Wheeler 1999; Armstrong 2000; Kortright and Wakefield 2010; Calvet-Mir et al. 2012a; Reyes-García et al. 2012). Private home gardens are performed in diverse spaces, such as backyards, balconies or terraces. However, literature has only focused on home gardens in backyards (Kortright and Wakefield 2010; Calvet-Mir et al. 2012b; Taylor and Lovell 2013) rather than in rooftop home gardens.

Notwithstanding that one of the main motivations behind home gardens is reducing the ecological footprint (Howe and Wheeler 1999; Armstrong 2000; Kortright and Wakefield 2010), home gardens have not yet been analyzed from an environmental impact perspective. To date, literature has dealt with the environmental impact of certain production systems and the estimation of the environmental savings of large-scale implementation, beyond other agronomic issues, such as the contribution to urban food security (Orsini et al. 2014). Food production in commercial rooftop greenhouses (Sanyé-Mengual et al. 2015a) and community rooftop gardens (Sanyé-Mengual et al. 2015b) has been quantified from a life cycle perspective. Although the avoided impacts of food imports were assessed for community farming in London (United Kingdom) (Kulak et al. 2013)and for rooftop farming in Singapore (South Korea) (Astee and Kishnani 2010), estimations were based on environmental data from conventional agriculture rather than specific calculations for urban food systems.

The assessment of local food systems has been mainly performed by applying the Life Cycle Assessment (LCA) method (ISO 2006a). A review of the LCA studies that compare local and imported food products is reported in Appendix 3.1. Most of the studies highlighted the potential environmental savings of local food production due to the reduction of food-miles (Jones 2002; Blanke and Burdick 2005; Sim et al. 2006; Coley et al. 2009; Sanyé-Mengual et al. 2013; Sanyé-Mengual et al. 2015a), apart from off-season production where imported products yielded better (Basset-Mens et al. 2014). Studies mainly chose a single case for the conventional supply-chain, the selection of which was based on the market share. When comparing with multiple origins for the imported food, studies aimed to show minimum and maximum distances or worked at national level or with specific data from food retailers. This research proposes to examine the benefits of local production, by using detailed market data of the food imports in the specific geographic area and, thus, involving all the origins of imported vegetables. Furthermore, since UA is commonly open-air and thus seasonal, the assessment also integrates seasonality.

The general aim of this paper is to provide environmental data of home-grown food in private rooftop gardens while contributing to the methodological framework for assessing the environmental impacts of local food systems. The study then pursues three main objectives. First, quantify the environmental burdens of crop production in a private rooftop garden by applying the LCA method. Second, evaluate the relevance of using detailed market data in the assessment of local food products. Third, evaluate the relevance of seasonality in the assessment of local food products. To do so, a case study in the city centre of Barcelona is assessed.

## 9.2. Methods

### 9.2.1. Experimental trials

Experimental trials were performed from June 2014 to February 2015 in a18-m$^2$private rooftop garden of the city of Barcelona (Spain). As a representative case study of Mediterranean cities, climatic conditions of Barcelona are favorable for year-round open-air rooftop farming practices. Furthermore, Barcelona is a high dense city with limited land availability, where rooftop farming can play a key role in the development of urban agriculture.

The growing system used in the trial was soil-less production with perlite that was supplied with automatic fertirrigation which used tap water. Trials were performed for five crops including leafy and fruit vegetables: tomato (*Solanum lycopersicum* L.),lettuce (*Lactuca sativa* L.), beet (*Beta vulgaris* L. subsp. *vulgaris*), chard (*Beta vulgaris* L. subsp. *cicla.*) and cabbage (*Brassica oleracea* L.) (Table 9.1). Crop cycles are indicated in Table 1 as Days-After-Transplanting (DAT) values. Other vegetables and herbs were grown in the garden, although they were not included in this analysis.

***Table 9.1.*** *Crop yields and irrigation requirements in the experimental trials.*

| Crop | Season | DAT [days] | Yield [kg/m2] | Avg. Yield [kg/plant] | Irrigation [L/m2] |
|---|---|---|---|---|---|
| Tomato | Summer (Jun-Sep) | 89 | 13,6 | 3,39 | 230,30 |
| Lettuce (1) | Summer (Jun-Jul) | 31 | 3,0 | 0,74 | 56,03 |
| Lettuce (2) | Summer (Jul-Aug) | 42 | 2,5 | 0,63 | 129,95 |
| Lettuce (3) | Autumn-Winter (Sep-Feb) | 153 | 0,8 | 0,20 | 285,67 |
| Beet | Summer (Jul-Aug) | 42 | 6,9 | 1,74 | 129,95 |
| Chard | Summer-Winter (Jul-Feb) | 211 | 6,0 | 1,50 | 415,62 |
| Cabbage | Autumn-Winter (Sep-Feb) | 153 | 1,5 | 0,37 | 285,67 |

### 9.2.2. Life Cycle Assessment

Life cycle assessment (LCA) is an standardized method to quantify the environmental impacts of systems, products or processes, defined by the ISO (2006) as: “Life cycle assessment is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (i.e., consecutive and interlinked stages of a product system, from raw materials acquisition or generation from natural resources to final disposal”. The LCA method follows for main stages: goal and scope definition, inventory, impact assessment and interpretation. This section describes the goal and scope, Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) steps followed in the LCA.

### Goal and scope

The assessment is divided into two main analyses: the assessment of the home-grown food production and the assessment from a local product perspective. First, crop production is assessed by applying an attributional LCA with the aim of accounting for the environmental burdens of the home-grown food products. In this case, a cradle-to-farm gate approach is taken and the life cycle stages considered are those related exclusively to the local home-grown food pathway: auxiliary equipment (i.e., supporting structure, irrigation equipment, cultivation materials) and the crop inputs (i.e., energy, water and fertilizers) (Figure 9.1, Private rooftop garden system).

Second, the assessment aims to observe the consequence of producing and consuming home-grown products, which is identified as the substitution of conventional food. As a result, the system boundaries are expanded to include the avoided conventional food pathway. The system expansion is based on the food-miles concept (Weber and Matthews 2008) and only the transportation stage (i.e., food-miles, km) is included due to lack of specific LCI data for the other stages of the supply-chain (Figure 9.1, Avoided food-miles system).

In this case avoided food-miles are quantified for different scenarios in order to evaluate the relevance of detailed market data and seasonality in the assessment:

Single case, the avoided food-miles correspond to the distance to the most competitive origin for the specific food product

Annual average, the avoided food-miles correspond to an average distance calculated from annual detailed market data of the specific food product

Monthly average, the avoided food-miles correspond to an average distance calculated from monthly detailed market data of the specific food product

In the entire study, the analyses are performed for each individual crop (i.e., tomato, lettuce, beet, chard, cabbage) and the functional unit is 1 kg of product.

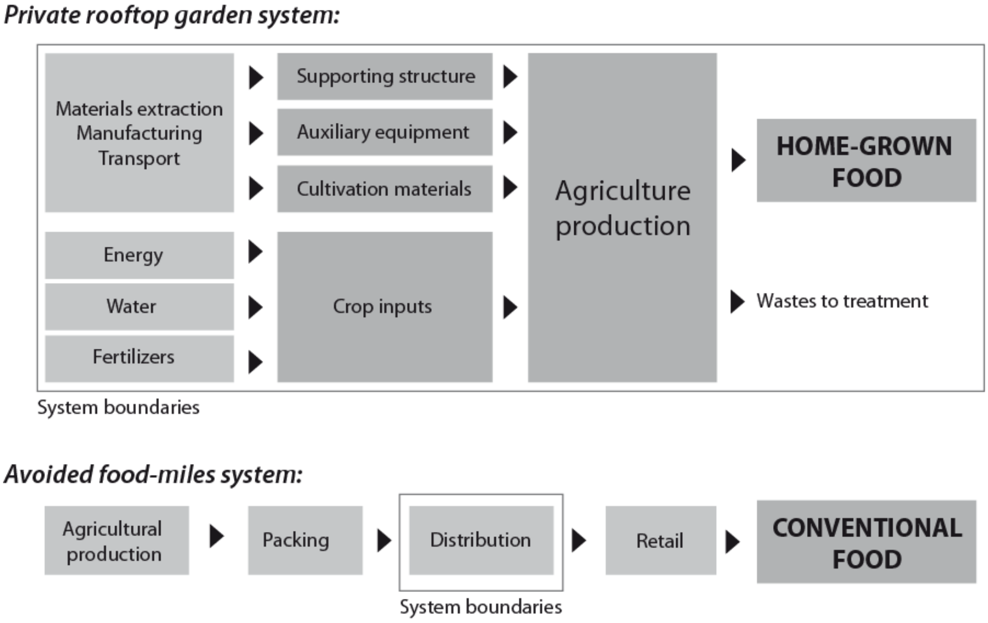


*Figure 9.1. System boundaries of the home-grown production system.*

### Life cycle inventory (LCI)

*(a) Local home-grown food pathway*

Foreground data is compiled from the experimental trials. Auxiliary equipment is locally sourced (<50km), apart from the substrate (i.e., perlite) which is imported from Almeria (Spain) (800km). In the waste management of the auxiliary equipment, the treatment is excluded from the analysis as materials are 100% recyclable (Ekvall and Tillman 1997) and, thus, only their transportation is considered (recycling plants are located 30 km away from the site). Detailed data on the auxiliary equipment is compiled in Appendix 3.2. Tap water is used for irrigation purposes and the electricity mix of Spain is used for the related energy consumption. The nutrient solution combines multiple fertilizers, as reported in Appendix 3.3. All crops are pesticide-free. LCI background data for materials extraction, processing, transportation and electricity generation are obtained from ecoinvent3.0 database (Swiss Center for Life Cycle Inventories 2014). Background data for the LCI of chemicals and fertilizers is completed with the LCA Food database (Nielsen et al. 2003).

*(b) Conventional food pathway*

The market database of the distribution food center of Barcelona (MercaBarna) (MercaBarna 2015) is used to account for the avoided food-miles (i.e., transportation requirements of the conventional food supply). Data of monthly food imports for the five products are collected from January 2010 to December 2014, which is used to calculate a 5-year annual average and 5-year monthly averages of the food-miles of imported conventional food to MercaBarna. LCI background data for transportation are obtained from ecoinvent3.0 database (Swiss Center for Life Cycle Inventories 2014).

### Life cycle impact assessment (LCIA)

The environmental impact assessment encompasses the classification and characterisation steps of the LCIA stage, determined as mandatory by the ISO 14044 regulation (ISO 2006b).The SimaPro 8.0.4 software (PRé Consultants 2013) is used to conduct the assessment. At the midpoint level, the methods applied are the global warming (GW, kg $CO_2$ eq.) (IPCC 2007), the water depletion (WD, $m^3$) and the ReCiPe-normalized (Goedkoop et al. 2009). Regarding the ReCiPe, the hierarchical time perspective is considered, as recommended in the ILCD Handbook (EC-JRC 2010). The three indicators are chosen due to the awareness of society (i.e., global warming), the relevance in the topic (i.e., water depletion) and the inclusion of a single score indicator to avoid trade-offs between environmental impacts (i.e., ReCiPe-norm).

## 9.3. Results and discussion

This section presents and discusses the results of the assessment by displaying the environmental burdens of home-grown crops, analyzing the distribution of the burdens among the diverse life cycle stages, and assessing the crops as local food system from a consequential perspective.

### *9.3.1. Environmental burdens of rooftop home-grown food*

Figure 9.2 displays the environmental burdens of the five crops under assessment. In general, fruit (i.e., tomato) and root (i.e., beet) vegetables had a better environmental profile than leafy vegetables (i.e., lettuce, chard, cabbage). This trend is also shown for all the Recipe midpoint indicators (Appendix 3.4). Tomato and beet obtained the highest crop yields and followed short crop periods. By the contrary, some leafy crops had low crop yields and were cultivated for longer periods. In particular, this trend can be observed in lettuce crops, which were performed in different seasons and obtained different yields. Compared to the previous ones, lettuce (3) was cultivated in winter, followed a crop period up to 5 times longer and had a low crop yield, resulting in an environmental impact between 7 and 9 times higher. Thus, the efficiency of crops is essential in determining the environmental burdens of home-grown food products and best management practices may be promoted among private rooftop gardeners.

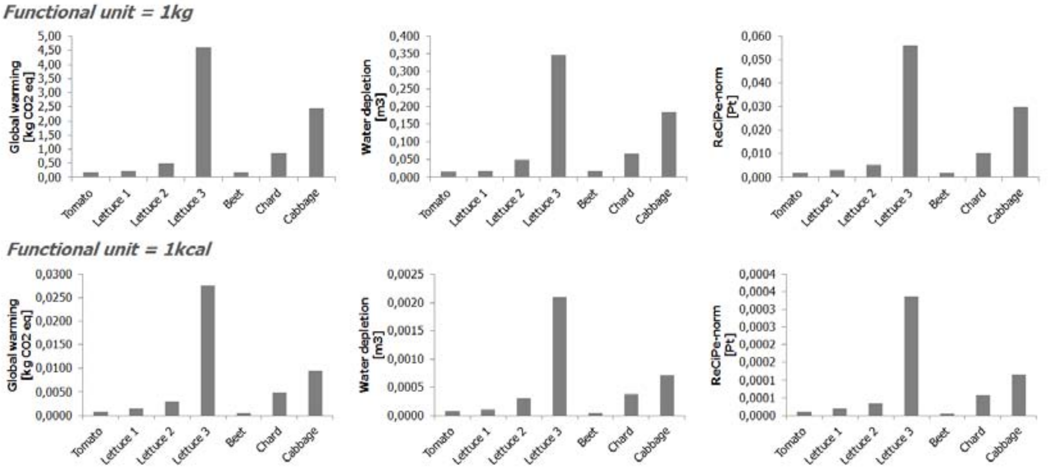


***Figure 9.2.*** *Global warming, water depletion and Recipe-norm value of the home-grown crops for a functional unit of 1 kg and a 1 kcal.*

The analysis of polyculture systems is limited since each crop has different properties. Figure 9.2 also displays the results for a functional unit of 1 kcal, in order to assess the different products in terms of nutritional value. In this case, fruit and root vegetables remained the most environmentally-friendly options. Beet had the lowest value in the environmental indicators as it has a higher caloric value (440 kcal·kg$^{-1}$) than tomatoes (211 kcal·kg$^{-1}$). Differences with lettuce are increased, as it has the lowest caloric value of the products under assessment (166 kcal·kg$^{-1}$) (Figure 9.2).

### Contribution of life cycle stages

The distribution of the environmental burdens among the different life cycle stages is presented in Figure 9.3. The most contributing stages to the environmental indicators were the fertirrigation and the structure of the garden.

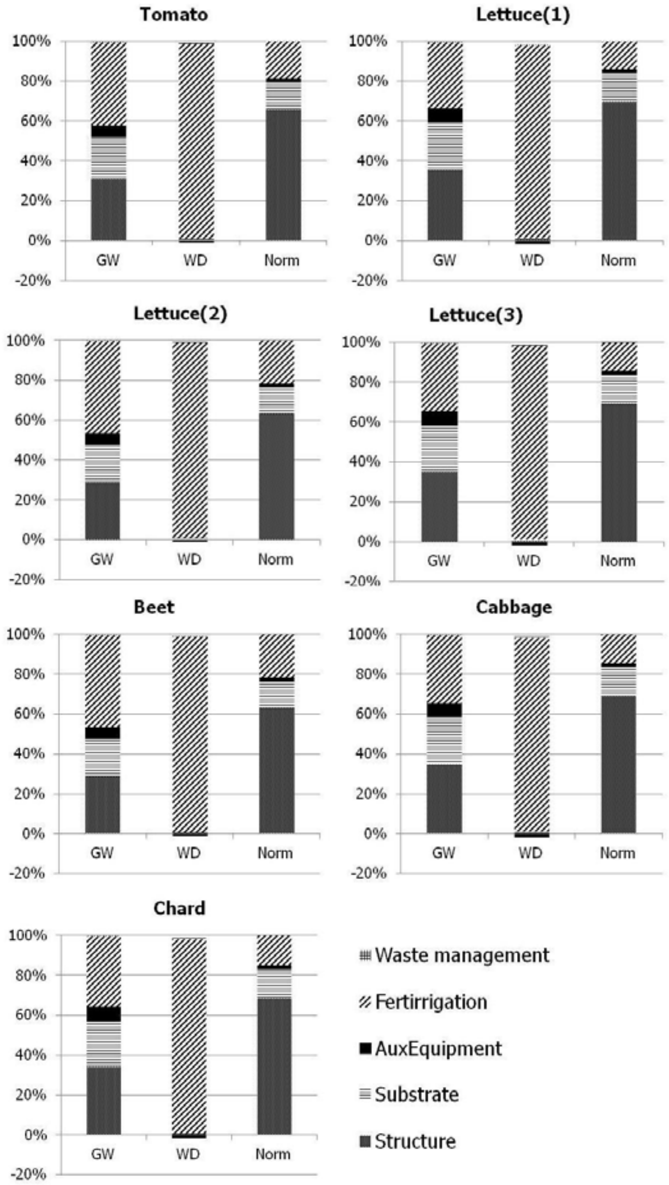


***Figure 9.3.*** *Distribution of the environmental burdens of home-grown crops among life cycle stages.*

Fertirrigation contributed to between 33 and 46% of the global warming impact, mainly due to the resources consumption in the production of some chemicals (i.e., nitric acid, calcium nitrate and potassium sulfate). The structure of the garden, made of wood and waterproof plastic, was responsible for between 28 and 35% of the global warming impact. Water depletion is produced in the fertirrigation stage of crops (~100%), where tap water is consumed. The impacts related to water consumption could be reduced by using local and renewable water sources, such as rainwater or wastewater from the building where the garden is located. For this purpose, the RTG-Lab (Bellaterra, Spain) takes advantage of the rainwater collected in the roof of the building, minimizing the consumption of tap water and related environmental burdens (Sanyé-Mengual et al. 2014; Sanyé-Mengual et al. 2015a).

A sensitivity assessment of the use of rainwater to supply the water requirements of the crop (Appendix 3.5) revealed that the effects of rainwater use in the environmental burdens are constrained, apart from water depletion. When the water crop requirements can be 100% supplied with rainwater, environmental burdens are reduced by up to 9%. On average, the decrease in the ReCiPe-normalized value, which reflects the different environmental indicators, is only of 3%. Notwithstanding this low effect, the use of rainwater could decrease the water depletion by 98%.

Structure is the most contributing element to the Recipe-norm value (63 – 69%), due to its relevance in the Recipe indicators associated to land use, eutrophication and ecotoxicity. These environmental burdens are related to the use of wood products and the forest management and sawmill processes. The design of private rooftop gardens can reduce the environmental burdens of such systems by integrating re-used elements, such as pallets, as already shown for community rooftop gardens (Sanyé-Mengual et al. 2015b).

### Comparison to reference production systems

Figure 9.4 displays the global warming impact of tomato and lettuce production for private rooftop farming, community rooftop farming, rooftop greenhouses and conventional production (minimum and maximum values).

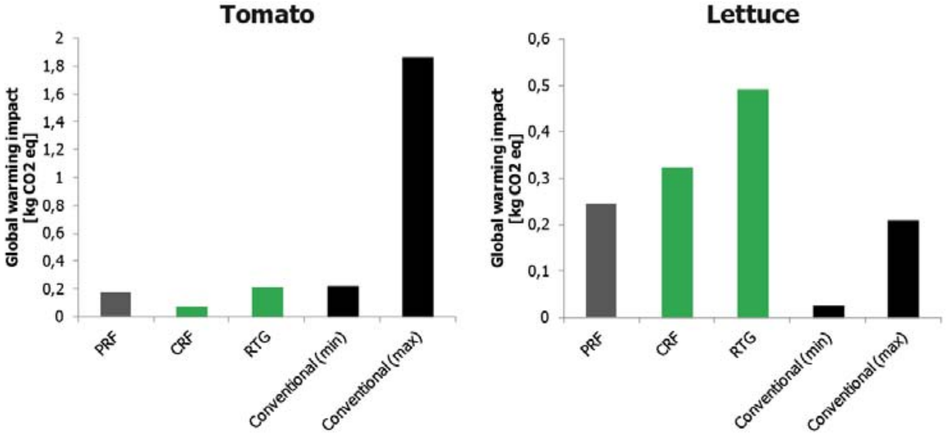


***Figure 9.4.****Comparison of the global warming impact 1 kg of tomato and lettuce from private rooftop farming (PRF) with community rooftop farming (CRF), rooftop greenhouses (RTG) and conventional production (minimum and maximum).*

Compared to other rooftop farming options, crops in the private rooftop garden showed a better environmental performance than commercial crops in rooftop greenhouses (Pou 2015; Sanyé-Mengual et al. 2015a). This relies on the technology employed in the case study. As an open-air farming system, the environmental burdens of greenhouse structures are avoided. When compared to crops in community rooftop gardens (Sanyé-Mengual et al. 2015b), results depend on the crop. In the case of tomatoes, the global warming impact of tomatoes from the private rooftop garden (0.178 kg $CO_2$ eq.) was higher than for organic tomatoes in the community garden (0.068-0.075 kg $CO_2$ eq.), but lower than RTG tomatoes (0.216 kg $CO_2$ eq.).

Home-grown lettuces had a lower global warming impact not only than rooftop greenhouses (0.492 kg $CO_2$ eq.) but also than the rooftop community garden (0.323 kg $CO_2$ eq.) (Figure 9.4). However, the crop yield of lettuce strongly varied among crop seasons and global warming can rise up to 4.59 kg $CO_2$eq (Figure 9.2). This issue highlights the sensitivity of the environmental profile of local food to crop yield and the need to ensure efficient crop management practices, as already shown in rooftop community farming (Sanyé-Mengual et al. 2015b).

Compared to conventional production, local home-grown tomatoes had a lower global warming impact than conventional production reported in the literature (0.22-1.86 kg $CO_2$ eq.) (Antón et al. 2005; Cellura et al. 2012; Torrellas et al. 2012; Page et al. 2012; Payen et al. 2015). However, home-grown lettuces showed a larger global warming impact (0.245 kg $CO_2$ eq.) than conventional soil production with different technologies (open-air, mulch, greenhouse) (0.025-0.209 kg $CO_2$ eq.) (Romero-Gámez et al. 2014) (Figure 9.4).

### Sensitivity assessment of non-commercial yield

The crop yield of home-grown production does not distinguish between commercial and non-commercial since gardeners tend to use all their production. Commonly, when the quality of the food is not suitable for raw consumption, they are devoted to produce added-value food (e.g., marmalade, sauces). Thus, crop yield in private gardens might be oversized when compared to commercial systems. To evaluate this potential bias, a sensitivity assessment was performed in the comparison of private rooftop farming with other types of urban agriculture and conventional systems. A variation of the percentage of non-commercial yield was included in the calculations of tomato and lettuce production. In the case of tomato, the percentage of non-commercial yield considered ranged from 0 to 20%, as plague attacks can result in high mortality. In the case of lettuce, the percentage considered was from 0 to 10%, since leafy vegetables have lower mortality rates. Figure 5 compares private rooftop farming (with different percentages of non-commercial yield), community rooftop farming, rooftop greenhouses and conventional production (minimum and maximum values) for tomato and lettuce production.

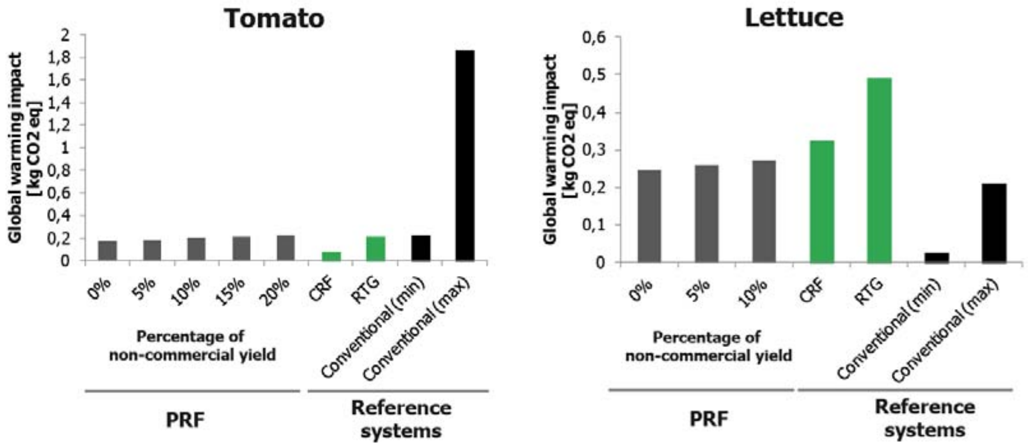


***Figure 9.5.****Sensitivity assessment to the percentage of non-commercial crop yield. Comparison of the global warming impact 1 kg of tomato and lettuce from private rooftop farming (PRF) with community rooftop farming (CRF), rooftop greenhouses (RTG) and conventional production (minimum and maximum).*

The assumption of a percentage of non-commercial yield revealed that the consideration of this parameter vary the environmental burdens of home-grown vegetables. Non-commercial yields up to 20% might increase the global warming impact of tomatoes by 25%. In this case, home-grown tomatoes from private rooftop gardens would have a larger impact than tomatoes from other rooftop farming systems (i.e., community rooftop farming and rooftop greenhouses) and than the minimum impact of conventional tomatoes (Figure 9.5). On the other hand, non-commercial yields up to 10% might increase the global warming impact of lettuces by 11%, thereby having a lower effect on leafy vegetables, which will keep as the most environmentally-friendly rooftop farming option although more impacting than conventional lettuces (Figure 9.5).

### Limitations of polyculture systems

Home gardens usually include different crops in the design of the garden (Kortright and Wakefield 2010). However, this issue can result in a limitation for some crops. In the case study, the garden followed a uniform design. The entire system was designed for fruit crops, in particular for tomatoes, leading to a plant density of 4 plants·m$^{-2}$, regardless the crop. Consequently, some crops were produced at a very low plant density, constraining the crop yield. Leafy and root vegetables could be produced at a plant density of 16 plants·m$^{-2}$, multiplying by 4 the outputs of the crop. An increase in the plant density for leafy and root vegetables could improve their environmental performance and become more environmentally-friendly options than fruit vegetables. For the case study, lettuce and beet production could have a lower global warming impact than tomato production (Figure 9.6). Thus, the division of the garden design into different areas could improve the sustainability of the entire rooftop garden, allowing the use of diverse plant densities and reducing the over consumption of certain inputs (e.g., water requirements could be sectorized by crop type according to specific demands).

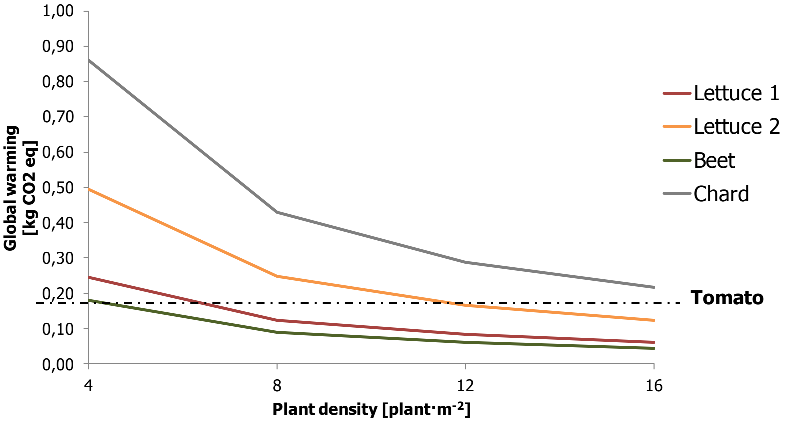


***Figure 9.6.*** *Sensitivity assessment of plant density for leafy and root vegetables for global warming impact (Lettuce 3 and cabbage were excluded for a better representation of results).*

## *9.3.2. Home-grown food from a local production perspective*

Figure 9.7 displays the avoided food-miles in terms of avoided global warming for the different products. In the assessment three approaches were compared when accounting for the avoided food-miles: a single case approach (i.e., the most competitive origin of conventional product), a annual average approach (i.e., considering all the origins during an entire year) and a monthly average approach (i.e., considering all the origins per each month).

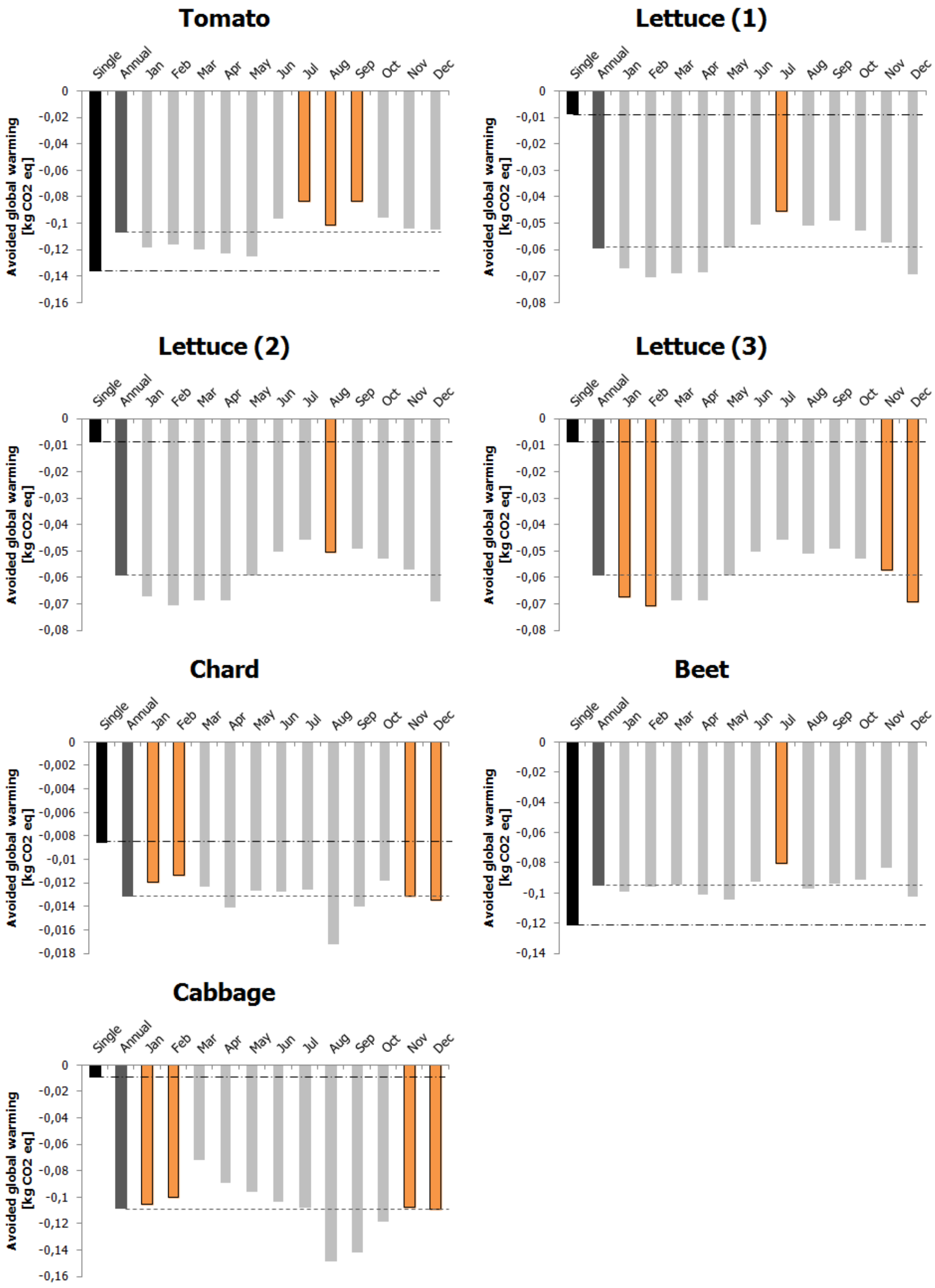


***Figure 9.7.*** *Avoided global warming impact due to avoided food-miles for a single case study, annual average and monthly average. The harvesting period is highlighted.*

### Relevance of complete market data: Single vs. entire market cases

The use of a consequential (single case) or an attributional (average market data) modeling in the environmental assessment with system expansion resulted in strongly diverse outputs. In general, the consequential modeling represented an overestimation or an underestimation of the attributional value. When Barcelona area is the most competitive region, the consequential modeling considered avoided food-miles of 50km. However, the use of average market data resulted in an avoided environmental impact between 2 and 13 times higher. Thus, cLCA lead to an underestimation of the benefits of producing locally. These are the cases of lettuce, chard and cabbage. By contrary, when regions other than Barcelona were more competitive, cLCA overestimated the benefits of home-grown food by between 25 and 31% (beet and tomato, respectively). Thus, aLCA offered a more accurate environmental accounting of the benefits of local production in terms of avoided food-miles (Figure 9.7).

This research used data from five consecutive years in order to avoid potential market biases. Some markets were more stable, such as beet or tomato, and annual variation was under 15%. However, some markets faced significant variations among years. In particular, the chard market was strongly sensitive to imports from South America and annual variation could result in up to 400%, when South America origins represented up to 6% of the total imports (Figure 9.7).

### Limitations of the "food-miles" concept

Notwithstanding the better understanding of the food market of this methodological approach, the use of the food-miles (i.e., only transportation) to account for the avoided impact of the conventional food pathway is a limitation of the study. Transportation might have a limited relevance on food supply-chains with energy-intensive production systems (e.g., United Kingdom, The Netherlands) (Edwards-Jones et al. 2008). In the case of tomato, the availability of LCA studies from different regions allowed to estimate the avoided impact of the conventional supply chain for the 5-year annual average. For 2014, the local production of tomato could represent environmental savings of around 0.29 kg $CO_2$ eq. Thus, the development of LCI data in the agricultural sector can support the completeness of the environmental burdens of the conventional supply-chains of vegetables in the accounting of the environmental benefits of local food systems.

### Relevance of seasonality: Annual vs. monthly data

Seasonality has been assessed from a consumer perspective in LCA studies by comparing local and imported food and considering preservation stages (Hospido et al. 2009; Foster et al. 2014; Macdiarmid 2014). The novelty of this paper relies on the assessment from a producer perspective, as the integration of monthly data in the assessment determines the avoided food-miles in the harvesting period. The variation between the minimum and maximum monthly avoided food-miles was between 43 and 87%. This represented a variation in the global warming impact between 35 and 66%, depending on the imports performed by ship, which had a lower environmental impact than freight road transportation (Figure 9.7).

As an open-air system, the case study harvested mostly on-season vegetables. In the case of tomatoes, on-season harvesting (July-September) represented an environmental impact 16% higher than the annual average. During the season, the regional area also increases the production of such vegetables and, thus, food-miles of imported tomatoes were reduced. For leafy vegetables, such as lettuce or chard, seasonality is less important as they can be produced mostly throughout the year. In those cases, the environmental burdens of on-season production were only increased by 1-4%, compared to the annual average.

Second, the relevance of seasonality also depends on the environmental impact of the product. The higher the environmental impact the lower the effect of the avoided food-miles. This trend is observed in the three cases of lettuce production, where the avoided food-miles had an insignificant effect (<0.5%) in the global warming impact of lettuce (3) crop.

Finally, the importance of the regional area in the market of the vegetables was also essential in the effects of seasonality. Barcelona area is the leader in the chard market for MercaBarna (≈80%, apart from 2014 where only represented 42%). Consequently, although some months importations are larger (up to 35%), the variation of food-miles is smaller than for other products where Barcelona area is not the leader of the market.

## 9.4. Conclusions

This paper contributes to the knowledge of urban agriculture and rooftop farming by providing further environmental data on private rooftop gardens in order to evaluate the sustainability of such local food systems. The environmental burdens of home-grown food from the rooftop garden were similar to those observed in other rooftop farming forms: rooftop greenhouses and community rooftop gardens (Pou 2015; Sanyé-Mengual et al. 2015a; Sanyé-Mengual et al. 2015b). Even more, some crops of the case study (e.g., lettuce) showed a better environmental profile than these forms. Compared to conventional food production, local food systems can yield better from an environmental perspective, depending on the crop and the growing technology. As expected by home gardeners (Howe and Wheeler 1999; Armstrong 2000; Kortright and Wakefield 2010), private rooftop gardens are a low environmental impact way to contributing to urban food security and the development of local food systems at the individual scale, within the global urban agriculture movement. The paper also highlighted the importance of the design of the garden in the environmental performance of home-grown crops, as polyculture gardens can limit the productivity of some crops (e.g., leafy vegetables).

A methodological contribution to the assessment of local food systems is here performed by proposing a more comprehensive analysis which includes the avoided conventional food that is substituted by home-grown products. When quantifying the avoided food-miles of local production, the integration of complete market data (i.e., origin of imported products) in the assessment by using average market data reduced the uncertainty, compared to using a single case. For fruit and root vegetables (i.e., tomato and beet), single cases overestimated the avoided food-miles between 25 and 31%, since the most competitive origin is not regional (>500km). For leafy vegetables, average market data indicated avoided food-miles between 2 and 4 times higher than single case.

A monthly assessment of the avoided food-miles offers a more precise analysis and, in the case of on-season production, avoids the overestimation of environmental benefits of local productions. Seasonality is particularly important for fruit vegetables and other vegetables that are not mainly produced in the study area, where monthly food-miles strongly vary between on-season and off-season periods. In these cases, off-season production showed larger environmental benefits, highlighting the potential role of protected farming in local food systems, such as rooftop greenhouses (RTGs).

Further research is needed in the assessment of urban agriculture and local food products. The inclusion of the social dimension in life cycle studies, the assessment of diverse forms of for-profit and non-profit urban agriculture systems and the sustainability assessment of urban agriculture at the city scale are research gaps that may shed light on the potential contribution to urban sustainability of such systems.

# Part V

# General conclusions and further research

# Chapter 10

# Conclusions and contributions

Picture: *Experimental rooftop (Paris, France)*
*(©Esther Sanyé-Mengual)*

# Chapter 10

This chapter outlines the main conclusions and contributions of this dissertation, which are divided into the answers to the research questions and the methodological and theoretical contributions.

## 10.1. Answering the research questions

This section answers the two research questions set out in the beginning of this dissertation and provides final remarks on the topic.

### Question 1: What is the potential of urban rooftop farming in qualitative and quantitative terms?

Urban rooftop farming shows a great potential in both qualitative and quantitative terms although at the mid-term since current development is still small-scale. The stakeholders' analysis performed in Barcelona (Chapter 3) suggested that the development of rooftop farming is currently limited because of lack of support and acceptance from some stakeholders.

This fact is mainly associated to the innovative aspects of such experiences:

- The lack of a common definition of urban agriculture, where some stakeholders even identify it as a false agriculture, make difficult to establish a framework where stakeholders can discuss and work towards the development of global urban agriculture policies and projects
- Contrary to the development for food security issues in North America, United Kingdom or Cuba, urban agriculture in Barcelona was developed for hobby purposes, leading into a conception that urban agriculture might be socially-oriented rather than commercial and, consequently, that soil-based urban agriculture is more interesting than rooftop farming
- Notwithstanding that some barriers and challenges were associated to the development of urban rooftop farming, stakeholders valued the potential environmental, economic and social benefits of urban rooftop farming in the context of the development of a local green economy
- The progressive development of urban rooftop farming through pilot projects and generation of new knowledge will increase the demonstration and dissemination towards a larger support of urban rooftop farming among stakeholders (Figure 10.1)

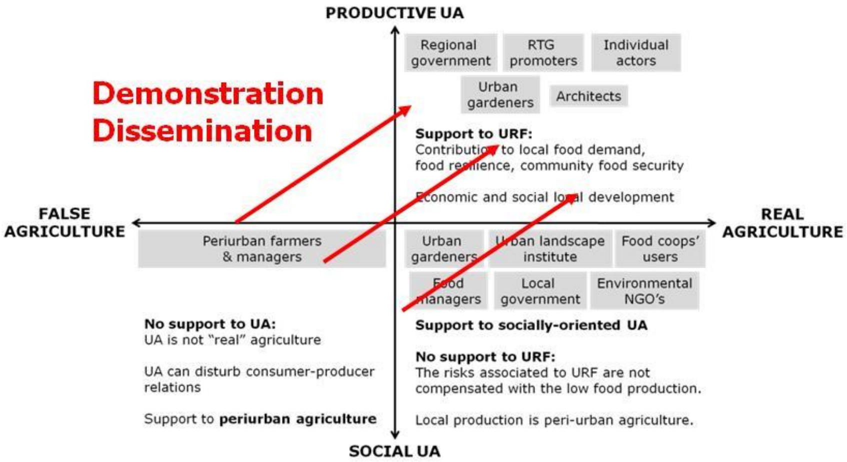


***Figure 10.1.*** *Stakeholders' position on conceptualizing UA and supporting URF in Barcelona, and expected trends through demonstration and dissemination activities.*

Once implementation barriers are overcome, rooftop farming shows an important potential in quantitative terms. Different urban areas and regions were assessed with the GIS-LCA method (Chapters 4 and 5). Results are the basis for implementation recommendations for urban planners, entrepreneurs and practitioners (Figure 10.2):

- The selection of suitable roofs for implementing rooftop greenhouses is a complex process where multiple criteria must be matched: availability of space, sunlight, resistance and slope, and legal and planning requirements.
- Retail parks show a greater short-term potential (53-98%, in the different cities assessed) than industrial parks (8%, in Barcelona) since the infrastructure of retail buildings (e.g., supermarkets, DIY stores) is more suitable due to the larger availability of flat and resistant roofs
- However, industrial parks are extensive urban areas and the potential implementation area is larger in these types of parks than in retail parks. Thus, a large-scale URF implementation plan can also benefit from such urban areas
- Effects of implementing rooftop greenhouses varies between warm regions (i.e., Spain, Portugal, Colombia, Brazil) and cold regions (i.e., The Netherlands, Germany), and the type of rooftop greenhouse (isolated or integrated):
- Regarding the preference between warm regions (i.e., Spain, Portugal, Colombia, Brazil) and cold regions (i.e., The Netherlands, Germany) for implementing rooftop greenhouses, the selection depends on the type of rooftop greenhouse and on the selective criterion:
    - Isolated rooftop greenhouses showed better crop yields in cold areas, since heated production in glasshouses (i.e., VENLO greenhouses) yields up to 56 kg·m$^{-2}$ compared to the efficiency of unheated greenhouses in warm areas (15-20 kg·m$^{-2}$). However, the environmental impact of heated production is higher than unheated production due to the energy requirements. Thus, cold or warm areas are preferable depending on whether food security or environment is prioritized (Figure 10.2).
    - When rooftop greenhouses are integrated and food production takes advantage from the residual flows from the building (i.e., heat, water, $CO_2$), trends are the opposite. In cold areas, the residual heat from the building can become the source of heating to the greenhouse and, thus, energy consumption can be decreased. In warm areas, the benefit is an increased crop yield by using the residual heat and the residual $CO_2$. Then, again,

cold or warm areas are preferable depending on whether environment or food security is prioritized (Figure 10.2).

- The assessment of the quantitative potential was performed for rooftop greenhouses, which is the more restrictive rooftop farming form. The selection of roofs for implementing open-air rooftop farming would be more flexible, since the plots, raised beds and other growing systems can be adapted to the spaces available in roofs, for example

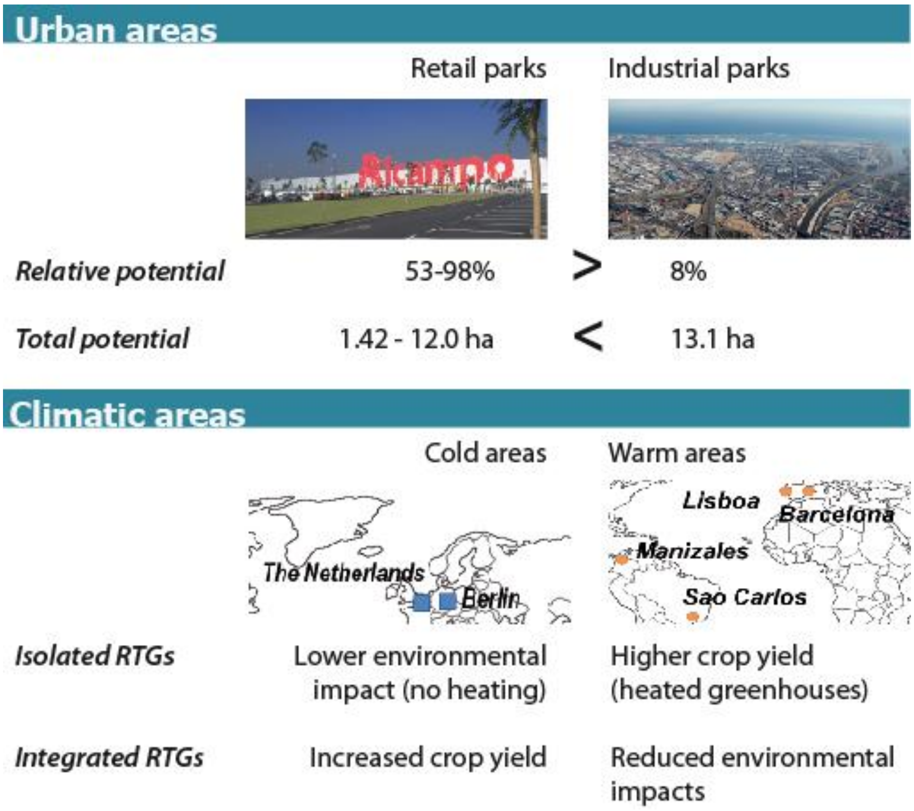


**Figure 10.2.** *Identification of suitable areas for implementing rooftop greenhouses.*

## Question 2: What are the environmental impacts and economic costs of urban rooftop farming systems?

Urban rooftop farming can become an environmentally-friendly option for further develop urban agriculture and local food systems in cities. However, results depend on the type of rooftop farming, the crop and the growing system. The pilot projects assessed in this dissertation (Chapters 6 to 9) unravelled some trends and drawn some recommendations for the development of rooftop farming.

### (2a) Deepening in the different forms of rooftop farming

The case studies analysed are pilot projects and this thesis offers the first environmental and economic results on urban rooftop farming. Outputs show some trends and patterns of the environmental and economic burdens of rooftop greenhouses, community and private rooftop gardens:

- Rooftop greenhouses (Chapters 6 and 7):
    - As in conventional greenhouse production, the structure of the greenhouse is the most contributing element to the environmental burdens (41.0-79.5 %), apart from some categories where fertirrigation plays the major role, as well as it is the most expensive stage (64%).
    - Although the greenhouse structure of RTGs have greater environmental impacts than multi-tunnel greenhouses (between 17 and 75 %), tomatoes from an RTG in Barcelona are more environmentally-friendly not only at the production point (between 9 and 26% lower) but also at the consumer (between 33 and 42 % lower).
    - From an economic perspective, RTGs are 2.8 times more expensive than multi-tunnel greenhouse and the production cost of tomatoes is 21% higher. However, when accounting for the costs of the entire supply-chain (i.e., including the transport, packaging and retail stages), local RTG tomatoes are 21% cheaper, making RTGs a competitive local food system.
- Community rooftop garden (Chapter 8):
    - Crop inputs are the most contributing stage in community rooftop farming (85% of the environmental burdens), where irrigation play the major role (60-75%). Crop inputs and the auxiliary equipment for the irrigation are the main costs of the production system.
    - As a common practice in urban agriculture and community initiatives, community rooftop garden takes advantage from re-used elements for constructing their cultivation systems, reducing the resources consumption and environmental burdens of these elements.

      From the economic perspective some crops (e.g., lettuce) are more expensive than current market prices due to the costs of tap water consumption. However, social externalities might be included in further economic balances, such as hobby, community building or education.
- Private rooftop garden (Chapter 9):
    - The main contributors to the global warming impact of food production are the fertirrigation (between 33 and 46%) and the structure of the garden (between 28 and 35%). Regarding water depletion, tap water consumption is produced in the fertirrigation stage of crops (~100%).
    - Rainwater harvesting for supplying the water demand of the crops and the integration of re-used elements in the cultivation structures, such as pallets, might enhance the sustainability of private rooftop gardens by decreasing the resources consumption of the system.
    - The inclusion of seasonality in the assessment of the environmental burdens of home-grown products reduces the uncertainty on accounting for the avoided food-miles, which is higher for fruit vegetables (e.g., tomato) than for leafy vegetables.

### (2b) Comparing rooftop farming forms and conventional production

The integration of the results from the pilot projects assessed in this dissertation (Chapters 6 to 9) show some trends regarding the comparison among urban rooftop farming forms (Figure 10.3):

- Open-air rooftop farming (both community and private) showed a better environmental profile than rooftop greenhouses, due to the environmental burdens related to the greenhouse structure. The same trend was shown for the economic cost.
- Between open-air farming forms, results depend on the crop type, the season and on the growing technique employed.
- Notwithstanding the observed trends, one may note that each type of rooftop farming aims to address different issues. Thus, although rooftop greenhouses showed larger environmental burdens, companies can benefit from a more-controlled environment and from the potential transformation to integrated RTGs. On the contrary, socially-oriented or self-managed initiatives may prefer rooftop systems more simple, placed in an open and fresh environment.

When comparing the results of lettuce and tomato production in the different rooftop farming forms analysed with data from conventional production, some patterns are observed (Figure 10.3):

- Lettuce production in rooftop farming had a larger environmental burden than conventional agriculture, mainly due to an inefficient crop design. In open-air rooftop farming, different crops are performed simultaneously and crop design is based on fruit crops (e.g., tomatoes) although lettuce crops can have higher crop densities. In the rooftop greenhouse, the experimental trial with perlite bags was designed for tomatoes leading also to a low crop density for lettuces. Thus, a higher crop density could be performed reducing the environmental burdens by product, as the cultivation and auxiliary equipments are allocated to higher crop yields. Improving the crop design of lettuce production would then place the environmental burdens of rooftop farming in the range of conventional agriculture
- Tomato production in rooftop had a lower environmental burden than conventional agriculture. In the case of rooftop greenhouses, the expected increase in crop yield of integrated RTGs that take advantage from the residual flows of the building could positively affect the environmental burdens of this type of rooftop farming. An improvement in the crop yield of tomato production in RTGs could place rooftop greenhouses as the second best option and enlarge the environmental benefits when compared to conventional production

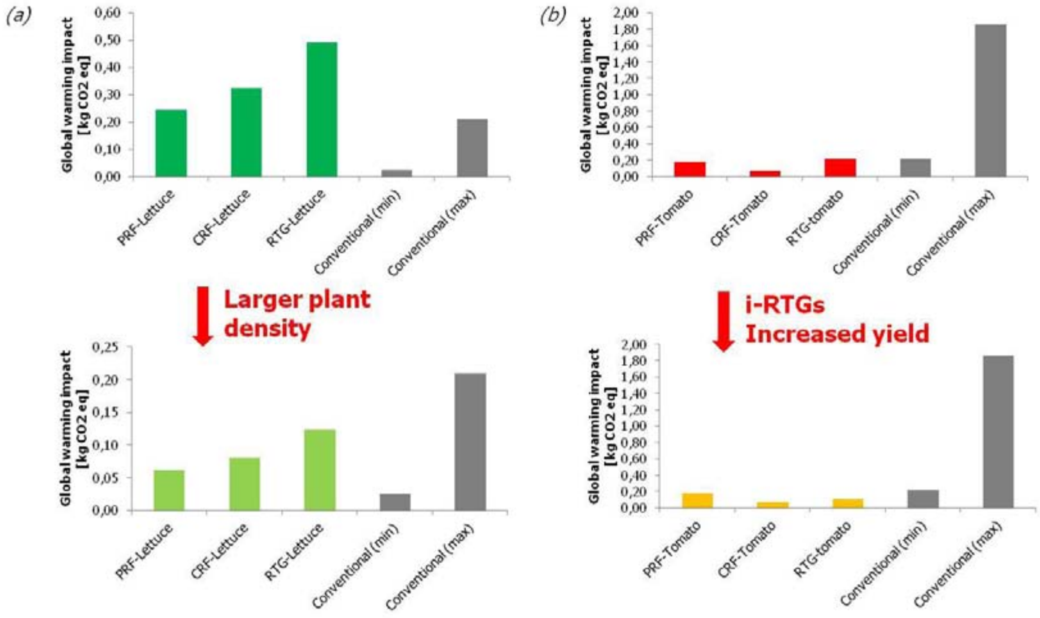


*__Figure 10.3.__ Comparison of the global warming impact of lettuce (a) and tomato (b) in rooftop greenhouses (RTG), community rooftop farming (CRF), private rooftop farming (PRF) and conventional production, and potential trends.*

*Note: Data of lettuce production in rooftop greenhouses is obtained from Pou (2015).*

### (2c) Prioritising growing systems and crops

The integration of the results obtained in the case studies (Chapters 6 to 9) draw some patterns regarding growing systems and crops (Figure 10.4):

- Soil production resulted in the most eco-efficient growing system for community rooftop farming, when compared to hydroponic options: nutrient film technique (NFT) and floating technique. In particular, NFT technique was the least eco-efficient option due to the electricity of the re-circulation pump and the associated environmental burdens (75% of burdens).
- Although soil-less tomato production in rooftop greenhouses had larger crop yields (25 kg·m$^{-2}$), it resulted less eco-efficient than soil production in the community garden (14 kg·m$^{-2}$) mainly due to the higher costs of the greenhouse system (11.9€·m$^{-2}$).
- Soil production in the community garden performed organic production using compost. This technique is able to integrate the organic wastes benefiting the urban metabolism.
- Beyond the environmental burdens of each growing system, gardens and farms can combined multiple systems for different stages of the crop production. In the community garden of Via Gandusio, floating hydroponic is now used for the first period of the plant which is then transplanted to soil containers.
- Fruit vegetables yielded better than leafy vegetables in all the analysed systems. Although leafy vegetables require a shorter crop period, the total yield is lower and environmental impact per kg of product is higher.
- However, the crop design of the case studies showed a gap for leafy vegetables, since all of them were prepared for crop densities for fruit vegetables, which are lower than for leafy

vegetables. Thus, the production of leafy vegetables with an adequate crop design (e.g., larger crop density) can reduce the environmental burdens of these products and reduce divergences among crop types.

- With regard to crop planning, one may note that a polyculture design is essential in community and private gardens which look for a variety of crops to satisfy their vegetables demand. On the contrary, commercial initiatives may prefer monoculture crops to specialize in an specific vegetable's market.

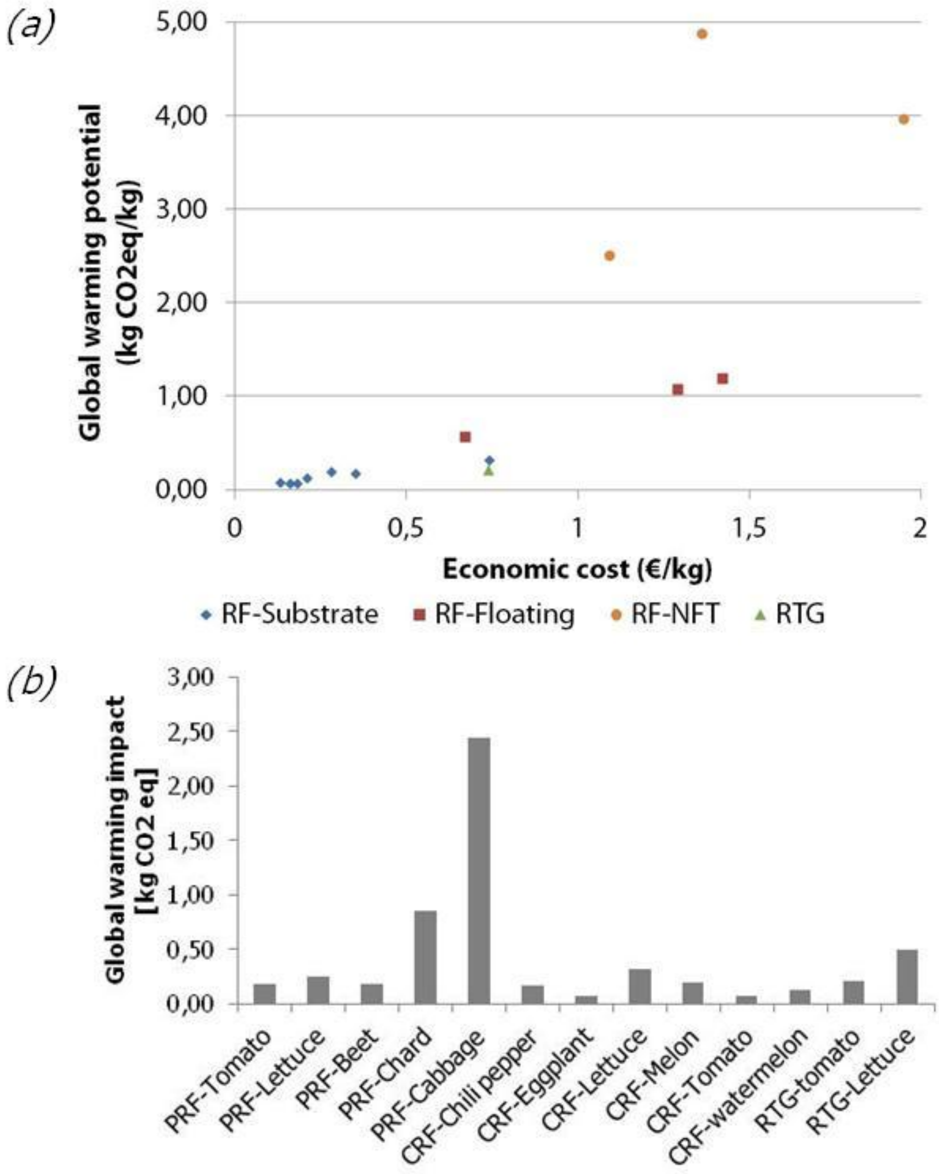


***Figure 10.4.*** *(a) Eco-efficiency of crop production in rooftop greenhouses and community rooftop farming and (b) Comparison of the global warming impact of crop production in rooftop greenhouses (RTG), community rooftop farming (CRF) and private rooftop farming (PRF).*

## Final remarks on the role of urban agriculture in cities

Rooftop farming can positively contribute to urban sustainability and urban food security since their environmental impacts and costs indicate that they are a feasible option to further develop urban agriculture and local systems. Notwithstanding these potential benefits, it is important to make clear that urban agriculture and local production in developed countries play a different role than in developing regions, where these types of food production are crucial for food security and survival.

In this sense, urban food systems are only expected to be complementary to the conventional agriculture sector which supplies the current vegetables market. Anyhow, the increase in local production experiences, such as rooftop farming, can cover the growing demand of local products. Furthermore, one may also consider that urban agriculture is multifunctional (e.g., social inclusion, education, biodiversity) and addresses multiple urban issues beyond food production. This important contribution to society was not quantified in this dissertation and further studies related to these social functions would largely contribute to the current knowledge.

## 10.2. Contributions of this dissertation

Finally, this section outlines the methodological and theoretical contributions of this dissertation. These contributions support the development of further studies on the topic of rooftop farming, urban agriculture and local food systems.

### (i) Methodological contributions

First, the thesis as a whole proposes a new methodological scheme. The interdisciplinary approach followed in this dissertation contributes to the assessment of urban sustainability strategies by providing a framework which encompasses tools to evaluate not only the context of urban development (e.g., stakeholders' analysis) but also the three dimensions of sustainability (i.e., society, environment, economy) and that is applied from the city to the system scales.

Second, resulting from Chapter 4 and 5, the thesis contributes with the development of a specific tool for assessing the potential of rooftop greenhouses at the urban planning level by combining GIS with LCA indicators. Main contributions are the identification of a multicriteria set to identify feasible areas for implementing RTGs and the development of a set of indicators for the assessment that combines self-supply and environmental benefits.

Finally, resulting from Chapters 6 to 9, the thesis contributes to the development of life cycle methods and its application to local food systems. The use of case studies unravelled challenges on applying LCA and LCC methods and methodological adaptations were proposed. In chapter 9, life cycle modelling approaches (attributional and consequential) are compared for assessing the avoided impacts of local food production. Furthermore, a methodological approach to use market data and to integrate seasonality in the assessment of local food systems is proposed.

### (ii) Theoretical contributions

This thesis contributes to the comprehension of the development process of competitive and sustainable urban agriculture and urban rooftop farming in cities of developed countries, in the following aspects:

- the identification of the stakeholders involved in urban agriculture and rooftop farming displayed a stakeholder map
- the outline of the challenges that these systems are facing nowadays, such as the complexity of defining urban agriculture and the inclusion of rooftop farming, the multiple positions of stakeholders and the risks related to social acceptance
- the identification of perceived benefits and needed actions, which strongly supports policy-makers, practitioners and entrepreneurs in the overcoming of challenges
- the determination of suitable areas for the implementation of rooftop farming systems
- the description of case studies

Finally, this dissertation contributes to the knowledge and understanding of rooftop farming, urban agriculture and local food systems by providing new data in terms of:

- inventory data (e.g., water consumption)
- environmental data (e.g., global warming impact)
- economic data (e.g., costs)

These data is crucial for supporting decision-making processes in the design and development of future rooftop farming projects.

# Chapter 11

# Future research and strategies

Picture: *Researchers exploring emplacements for rooftop farming (Paris, France)*
*(©Esther Sanyé-Mengual)*

# Chapter 11

This chapter identifies future research lines around the topics analysed throughout this dissertation:

- Assessing the perceptions around urban rooftop farming (Chapter 3)
- Quantifying the potential of urban rooftop farming (Chapters 4 and 5)
- Sustainability assessment of urban rooftop farming (Chapters 6 to 9)

## 11.1. Assessing the perceptions around urban rooftop farming

The perceptions of the different stakeholders involved in urban agriculture and urban rooftop farming in cities are of great interest since they determine the development of such experiences by acting as promoters, policymakers, facilitators, opponents, investors, users or consumers.

### (i) Strategies to improve the perceptions around urban rooftop farming

- The multiple definitions of urban agriculture may be analyzed toward a **global definition of urban agriculture** that became a global framework for the understanding between stakeholders, where **urban rooftop farming forms might be integrated** to facilitate policy-making and decision-making processes.
- Further sustainability research on **rooftop farming** might:
  - demonstrate the **sustainability of rooftop farming**, increasing the promoters' interest (e.g., private investors, administration)
  - **overcome implementation barriers** (e.g., low environmental advantages, urban contamination, economic investment)
  - ensure the **development of sustainable local food systems**
- The development of **rooftop farming pilot projects** might:
  - approach citizens to urban rooftop farming forms, decreasing the citizens' distrust and, thus, increasing the **social acceptance** of these systems
  - demonstrate the **feasibility of rooftop farming**, increasing the investors' (both public and private) interest in both for-profit and non-profit projects
  - become case studies to **revisit current urban planning and building policies** in order to adapt them to such innovative urban agriculture forms

### (ii) Future research on perceptions around urban rooftop farming

Further research on this topic may focus on the following aspects:

- Assessment of **stakeholders' perception in different cities** where urban rooftop farming is being developed, in order to analyze the effect of geographic and socioeconomic factors and to observe global trends
- Deepen in the **social acceptance** of urban rooftop farming in order to understand the behaviours of users and consumers and the potential barriers that urban food projects can face.

Methodological proposals:

- Inclusion of the temporal variable through **dynamic studies** with the aim of observing changes and trends in stakeholders' perceptions and the effect of the development of rooftop farming projects.

## 11.2. Quantifying the potential of urban rooftop farming

The quantification of the potential of urban rooftop farming is essential for supporting policy-making and decision-making processes, in particular at the city level.

### (i) Strategies to improve the potential of urban rooftop farming

- Urban planners might prioritize the implementation of urban rooftop farming in areas with a **larger potential** (e.g., retail parks are more recommended than industrial parks)
- Revisit the **current legal framework** to include rooftop farming in urban planning and building codes might weaken current barriers for URF deployment

### (ii) Future research on perceptions around urban rooftop farming

Further research on this topic may focus on the following aspects:

- Apply the GIS-LCA method for quantifying the potential of other **forms of rooftop farming**: private and community rooftop gardens in residential areas
- Assessment of other **areas of cities**, such as residential areas or other types of parks (e.g., knowledge parks, university campus).
- Inclusion of the **"patchwork" concept** in the proposed GIS-LCA method in order to assess the sustainability potential of combining multiple rooftop uses (e.g., photovoltaic production, rainwater harvesting, rooftop greenhouses, green roof)

Methodological proposals:

- Inclusion of further **sustainability indictors** in the GIS-LCA method, in particular economic and social indicators might be added to evaluate the three dimensions of sustainability
- Promotion of **remote sensing data** to automate the quantification process through GIS (e.g., rooftop slope from Lidar data - Laser Imaging Detection and Ranging)

## 11.3. Sustainability assessment of urban rooftop farming

Enhancing the development of sustainable urban rooftop farming is essential for guaranteeing the contribution to urban sustainability of these innovate local food systems.

### (i) Strategies to enhance the sustainability of urban rooftop farming

- General strategies:
    - the use of **renewable and local resources** (i.e., energy, water, wastes, and emissions) might decrease the consumption of non-renewable resources and the related sustainability impacts and costs.
    - **rainwater harvesting systems** can be applied to all forms of urban rooftop farming while decreasing the consumption of tap water and providing environmental services to cities, such as storm water management.
    - in soil production, the integration of **urban wastes** can be performed by composting the organic fraction and using it as organic fertilizer.
    - ensure **short supply-chain schemes** with **sustainable packaging options** to minimize the contribution of the distribution stage to the sustainability impacts
    - enhance **inclusive rooftop farming models** to address social gaps in urban areas and to boost local involvement in local food systems
- In the case of rooftop greenhouses:
    - **lighten and eco-design the greenhouse structure**, which is the main contributor to the environmental impacts and costs
    - the integration of rooftop farming current policies might revisit current **legal requirements** that increase the environmental impact and costs of rooftop greenhouses (e.g., higher resources consumption)
- In the case of community and private rooftop gardens:
    - the inclusion of **re-used elements** in the garden design decreases the consumption of resources and costs
    - the design of polyculture gardens might include **sectorization of irrigation systems** in order to adapt the resources requirements (i.e., water, fertilizers) to each type of crop, for example gardens might be divided between fruit and leafy vegetables
    - the improvement of **agricultural knowledge** of gardeners might improve the efficiency, in particular in the use of crop inputs (e.g., water, fertilizers)
    - an **efficient crop planning** might consider the best season for each crop in order to enhance crop yields and reduce

### (ii) Future research on the sustainability of urban rooftop farming

Further research on this topic may focus on the following aspects:

- Further **case studies in rooftop farming** might enlarge the knowledge of the sustainability performance of crops, growing system, rooftop farming forms. In particular, the following aspects are of great interest:
    - the assessment of **commercial case studies** (e.g., rooftop farms)
    - the use of **experimental data** in the assessment of rooftop greenhouses

  - the **sustainability performance of integrated RTGs** (i-RTGs) that exchange energy, water and gases
  - the analysis of case studies from **different regions**
- Further **case studies in vertical farming** might provide new knowledge of the sustainability performance of other innovative forms of local production (e.g., indoor farming, aquaponics)
- Further **case studies in urban agriculture** and other local food systems might provide data to contextualize the sustainability profile of urban rooftop farming (e.g., allotments, community gardens)
- The assessment of **business models and economic feasibility** used in urban agriculture in order to evaluate rooftop farming projects from a cradle-to-consumer perspective (e.g., CSA, coops)

Methodological proposals:

- The application of life cycle assessment to urban rooftop farming might focus on the development of **social-LCA indicators** and studies on the topic in order to cover the three sustainability dimensions, particularly for non-profit forms of URF
- LCSA studies might approach these metrics to the **multifunctional nature** of urban agriculture systems by revisiting allocation and functional unit parameters
- The creation of **sustainability tools and schemes** might support policy-makers, entrepreneurs and practitioners in the development of urban agriculture and rooftop farming experiences
- The **re-bound effects** of local food systems might be assessed from a consequential perspective by including the global market in the assessment

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# Appendixes

**Appendix 1.** Supporting information for chapter 5

**Appendix 2.** Supporting information for chapter 6

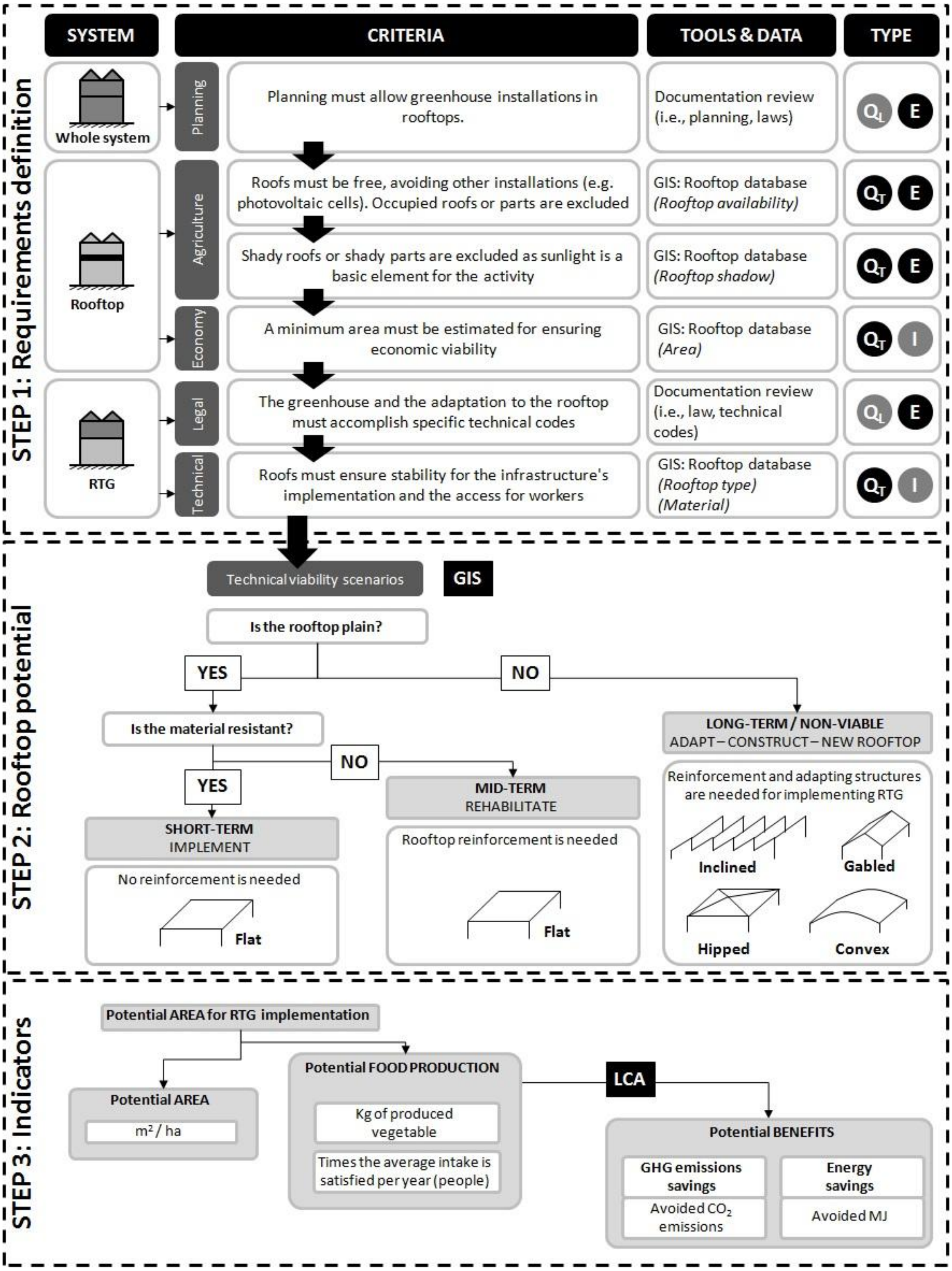
**Appendix 3.** Supporting information for chapter 9

# Appendix 1. Supporting information for chapter 5

Contents:

## Appendix 1.1: Scheme of the guide for assessing the implementation potential of Rooftop Greenhouses (RTGs) in industrial and logistics parks.

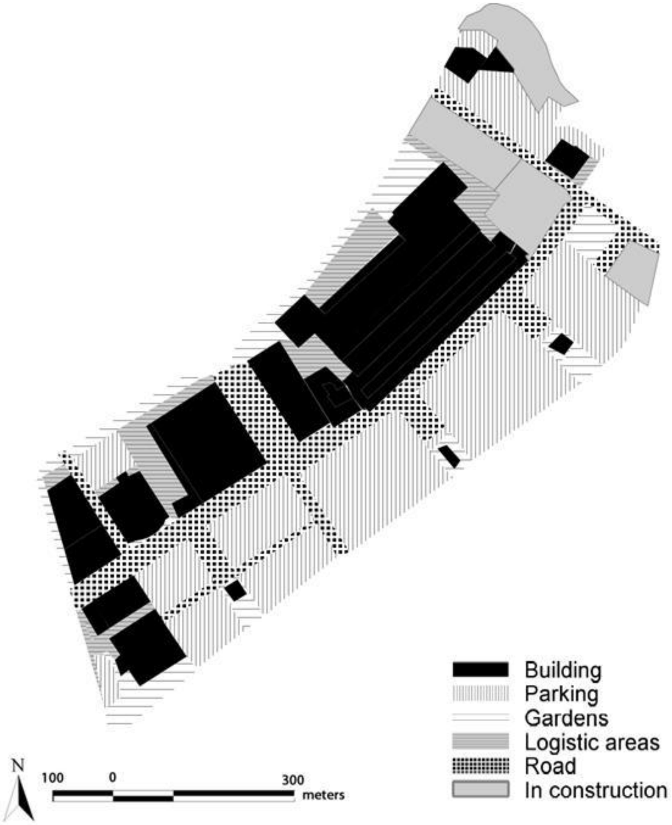
This figure shows the guide specifications, step by step, defined in Sanyé-Mengual et al. (2015). Criteria can be Quantitative ($Q_T$) or Qualitative ($Q_L$), regarding the type of data needed for validation; and External (E) or Internal (I), if the criteria depend on external conditions (e.g., law, third parts) or can be decided internally (e.g., economic outputs and RTG dimension).



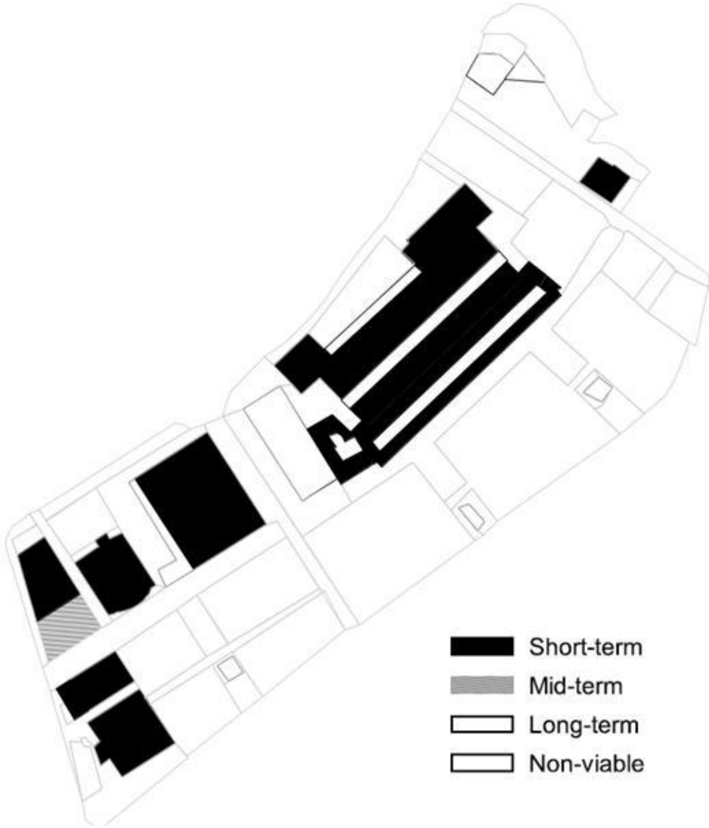
## Appendix 1.2: Land-use distribution and RTG potential maps of the case studies

The following figures show the land-use distribution and the RTG potential implementation of the different retail parks analysed.

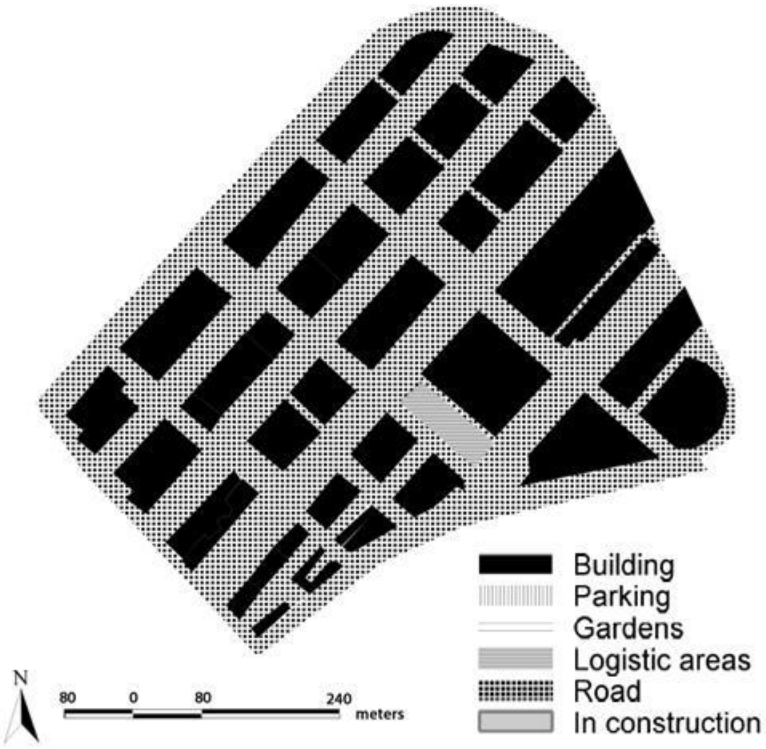
**Land-use distribution Sant Boi, Barcelona (Spain)**



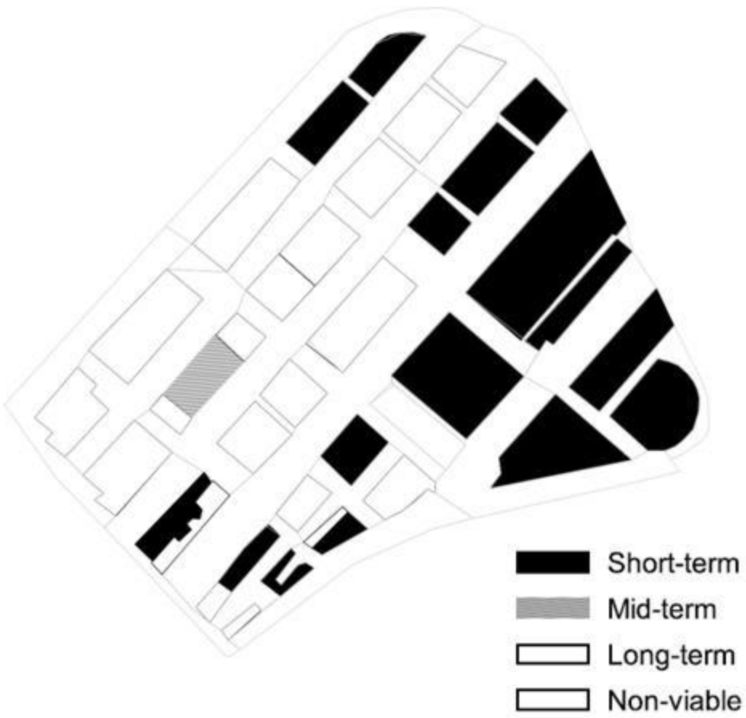
**RTG potential Sant Boi, Barcelona (Spain)**



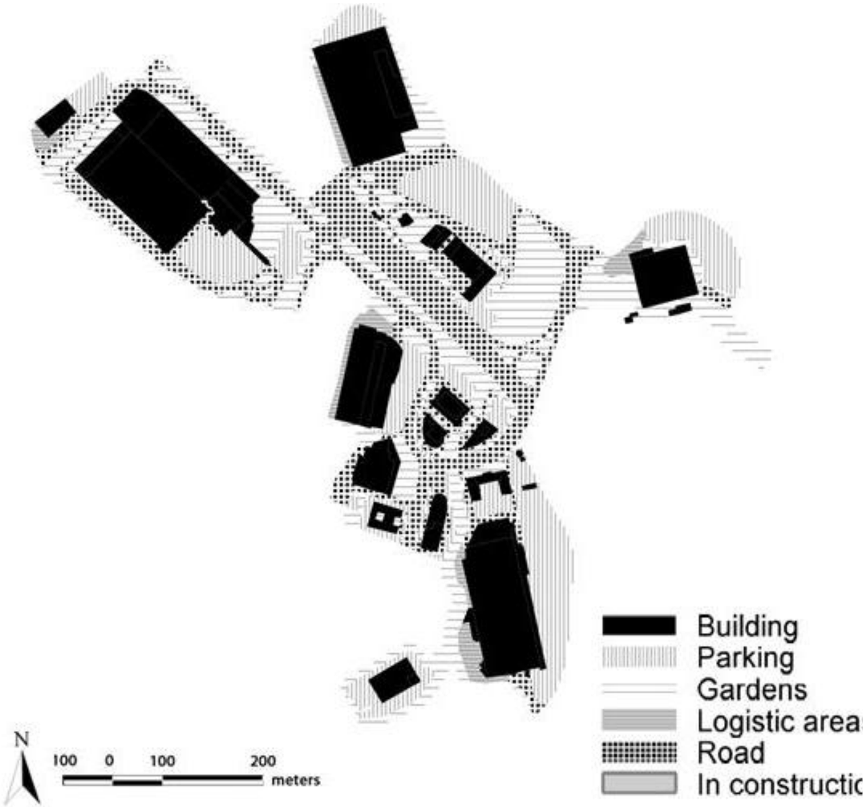
**Land-use distribution Montigalà, Barcelona (Spain)**



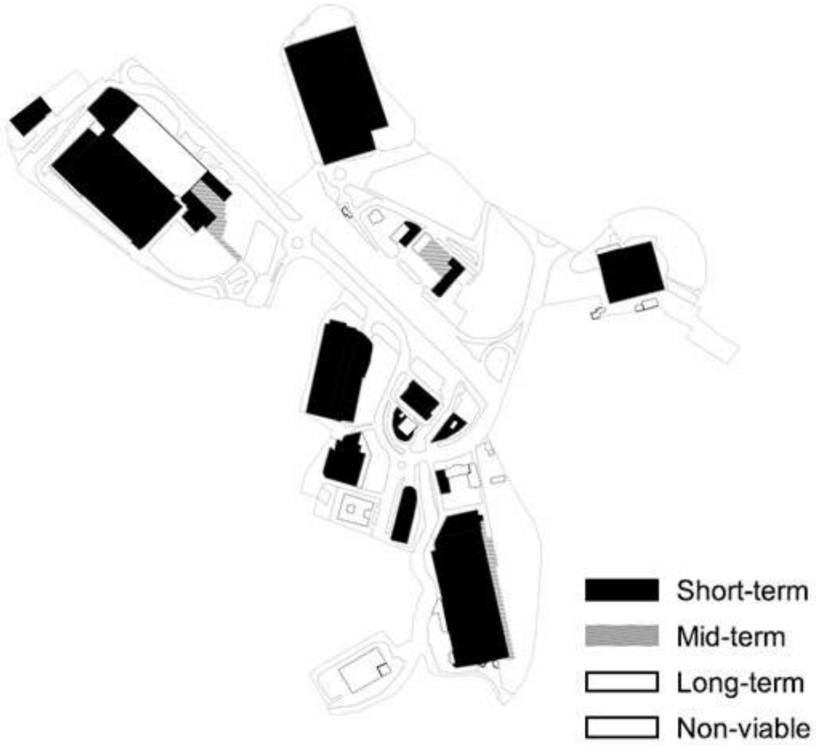
**RTG potential Montigalà, Barcelona (Spain)**



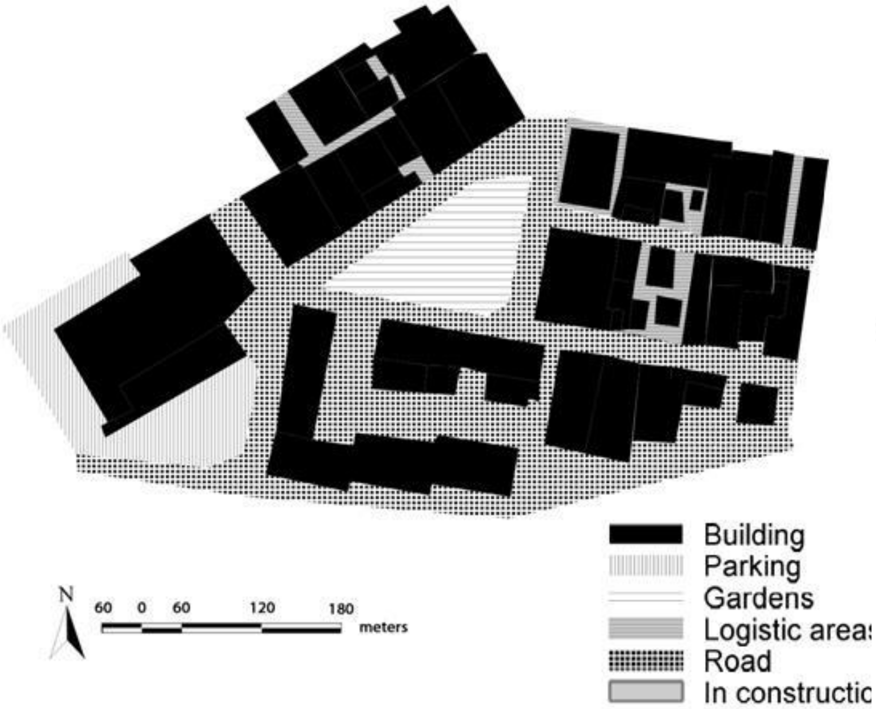
**Land-use distribution Alfragide, Lisbon (Portugal)**



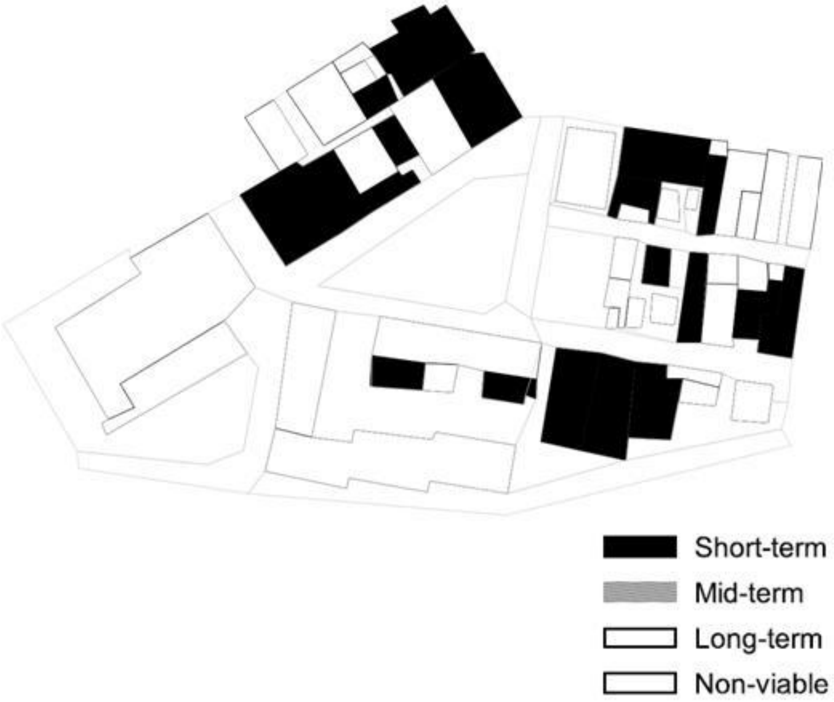
**RTG potential Alfragide, Lisbon (Portugal)**



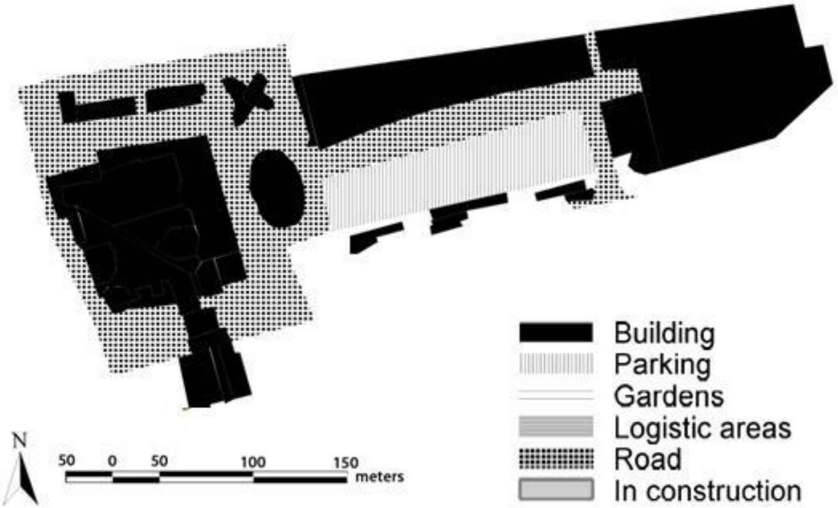
**Land-use distribution Utrecht (The Netherlands)**



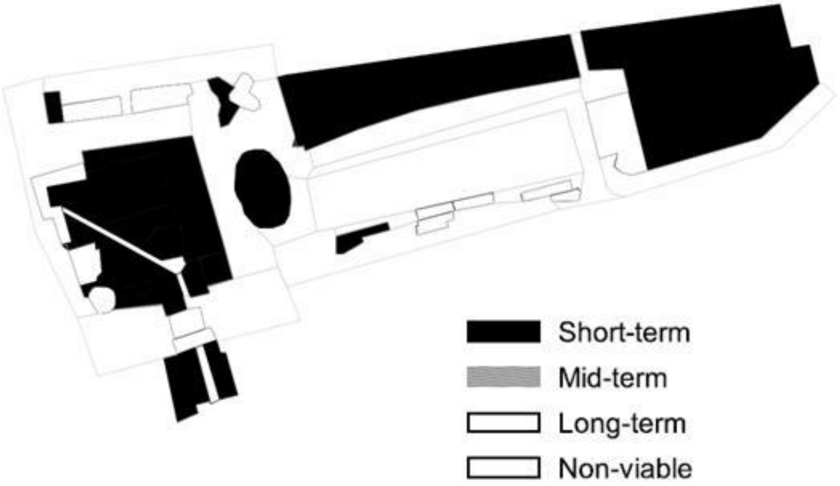
**RTG potential Utrecht (The Netherlands)**



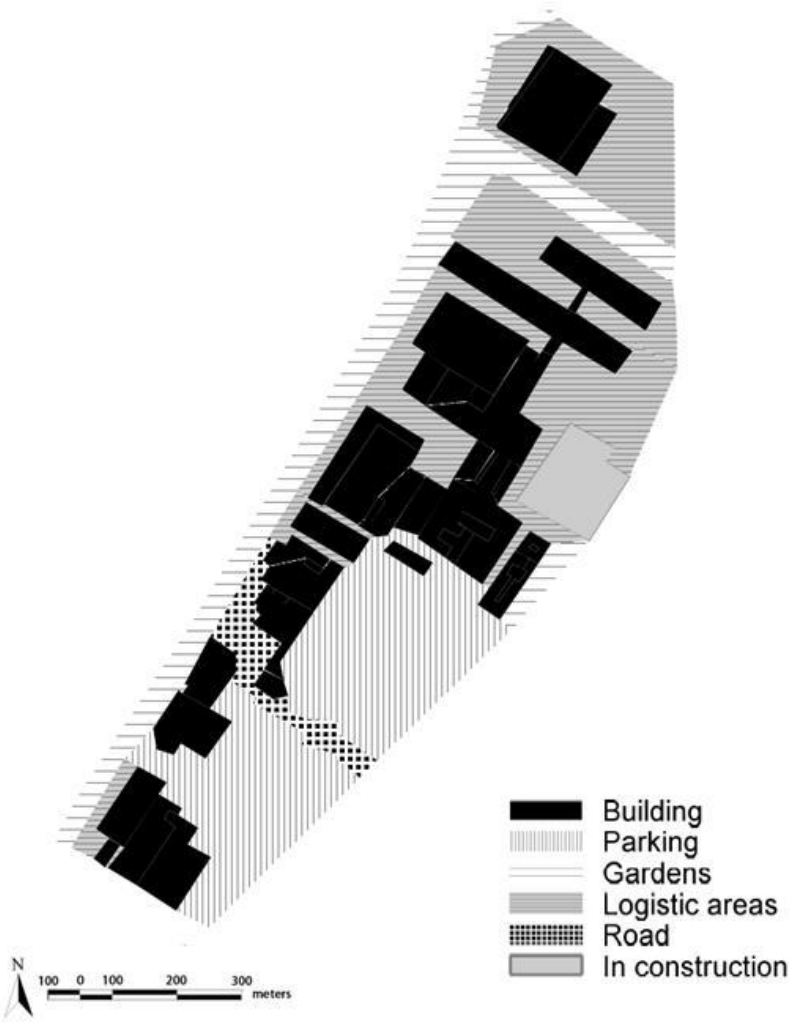
**Land-use distribution Rotterdam (The Netherlands)**



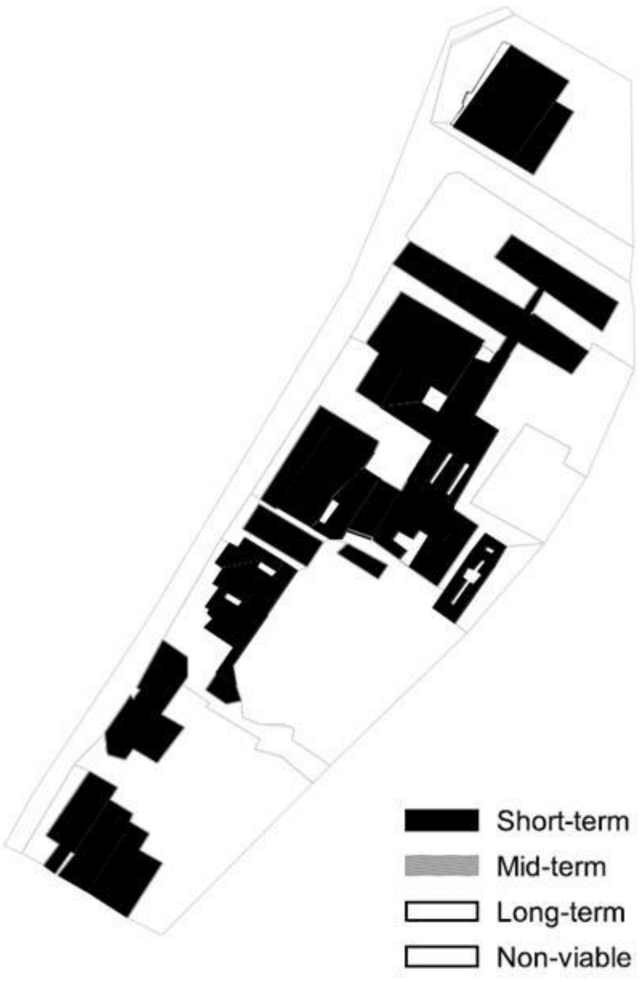
**RTG potential Rotterdam (The Netherlands)**



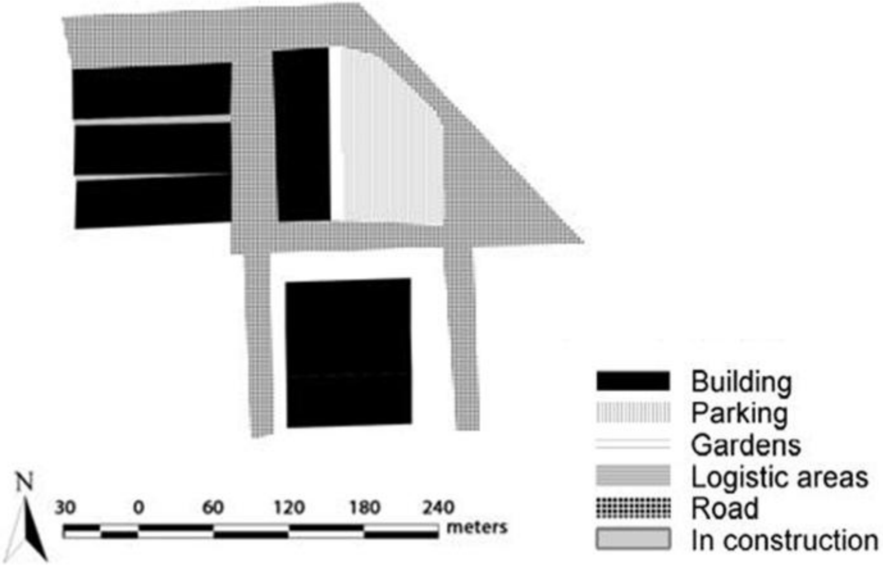
**Land-use distribution Berlin (Germany)**



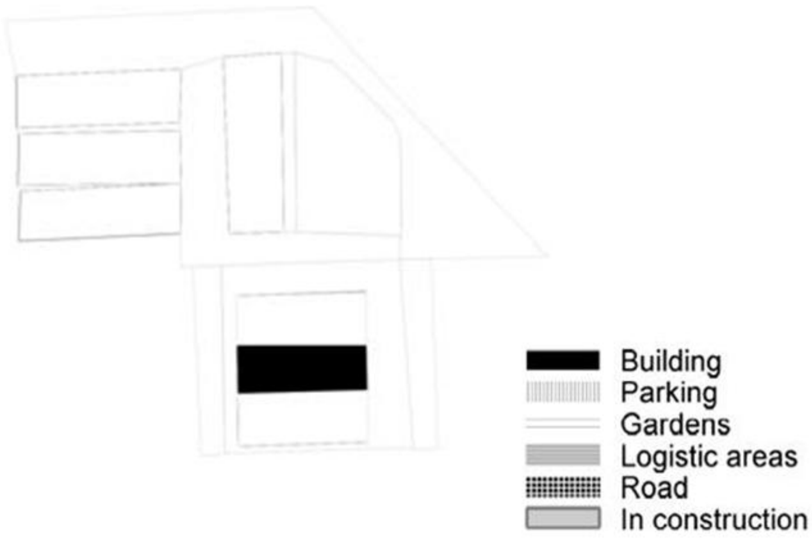
**RTG potential Berlin (Germany)**



**Land-use distribution Manizales (Colombia)**

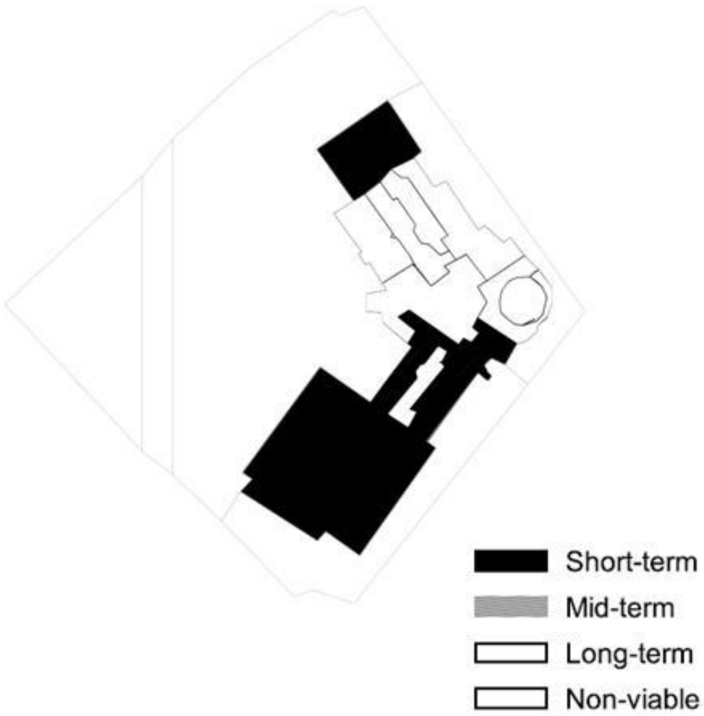


**RTG potential Manizales (Colombia)**



**Land-use distribution Sao Carlos (Brazil)**

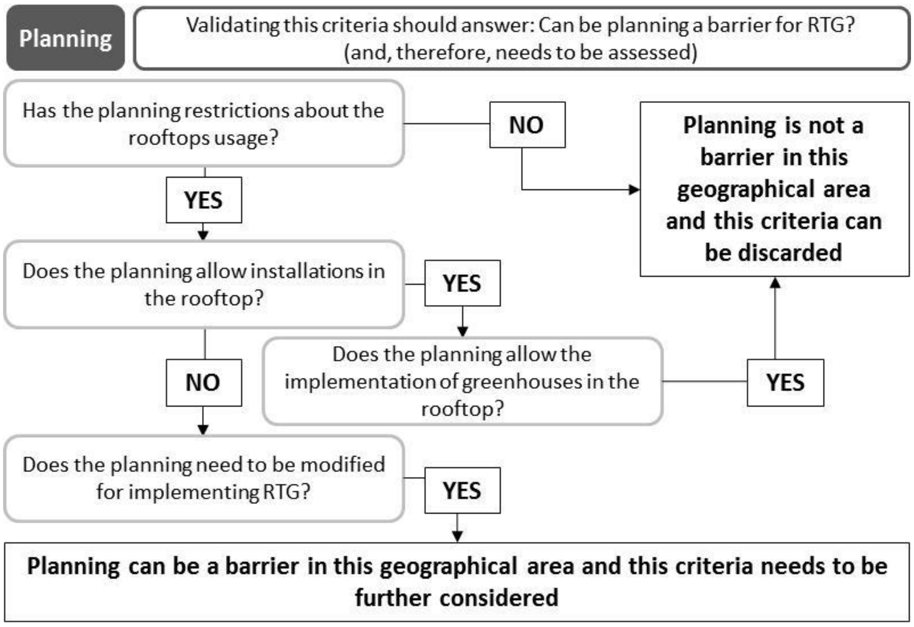
**RTG potential Sao Carlos (Brazil)**



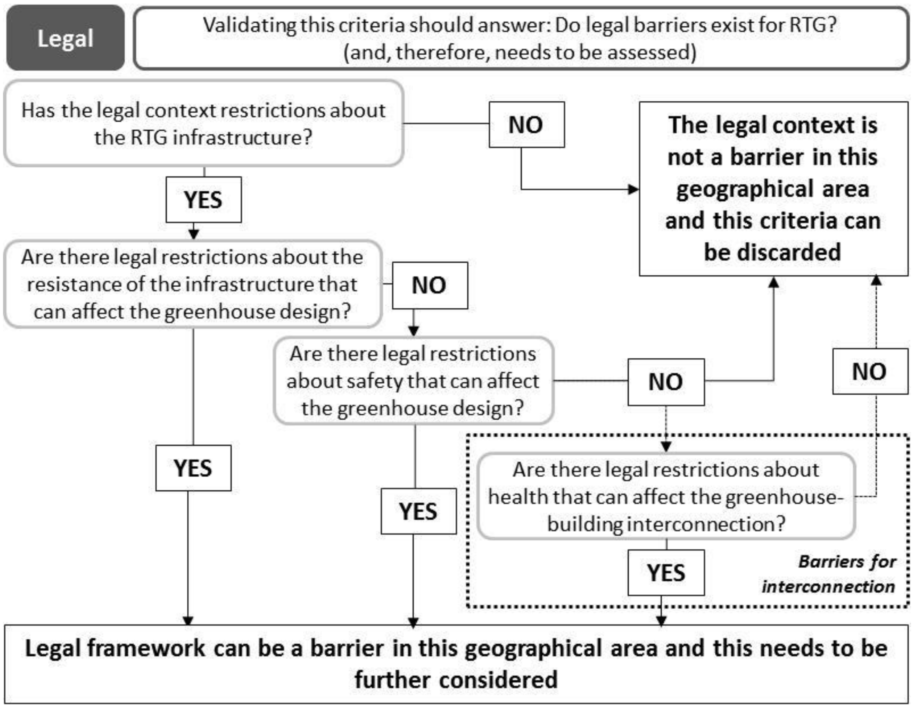
## Appendix 1.3: Standard process for criteria validation

The criteria identified as geographic-sensitive in Sanyé-Mengual et al. (2015) are planning, legal and economic conditions. In this sense, these three criteria were validated for the different study areas following standard Yes-No diagrams and consulting reference documentation (e.g., law documents). In the following figures are shown the Yes-No diagrams used in this validation process.

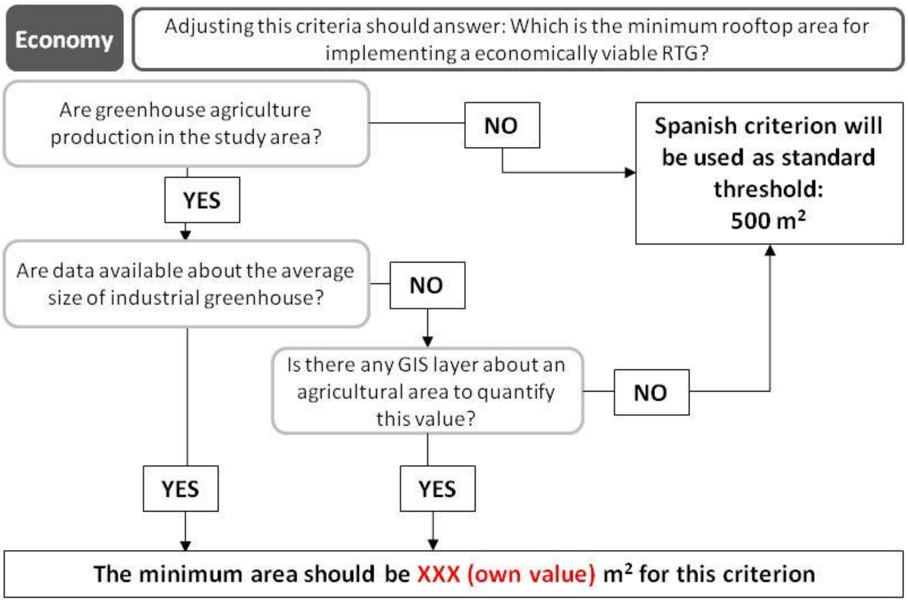
***(a) Validation of planning criteria:***



***(b) Validation of legal criteria:***



### *(c) Adjustment of economic criteria:*



## Appendix 1.4: Calculation of the environmental indicators for the case studies

In the following lines, the cultivation parameters and the variables used for accounting the environmental indicators (Step 3) are explained.

### (a) Cultivation systems of the different case studies

For this study, tomato was chosen since it can be cultivated in all the selected study areas and due to its importance in the different food markets. Due to different climate conditions, type of cultivation varies among the countries and therefore different cultivation parameters were used in the calculations. Therefore, greenhouse technology was considered to adapt literature data about greenhouse and horticulture production assessment. As Life Cycle Assessment (LCA) is used for quantifying the environmental burdens, Life Cycle Inventory (LCI) data from the EUPHOROS project (Montero et al., 2011) was used as follows:

- LCI data of the multitunnel greenhouse in Spain is used as LCI data for warm climates (Spain, Portugal, Colombia and Brazil), where unheated technologies are employed
- LCI data for the VENLO greenhouse in The Netherlands is used for cold climates (The Netherlands, Germany)

Based on these inventories, LCI data was adjusted according to:

- The cut-off perspective that considers that recycled materials obtained from the market are accounted as 0 input as material, although transforming processes must be considered, as well as waste for recycling is not considered as assumed to be accounted in future life cycles (Ekvall and Tillman, 1997)
- The last data about the electricity production mix for each country: Spain (REE, 2013), Portugal (REN, 2013), The Netherlands (CBS, 2013a, 2013b), Germany (BDEW, 2013), Colombia (UPME, 2013) and Brazil (MME, 2013)
- The cultivation parameters referring to productivity, water consumption and heating demand (Table 1)

### (b) Cultivation parameters for isolated RTGs (Scenario A)

The implementation of isolated RTGs (Scenario A) considers that RTGs use the conventional greenhouse technology of the different study areas. The cultivation parameters for the calculation of the environmental impact were obtained from literature data, as shown in Table 1. The application of fertilizers and pesticides are obtained from the EUPHOROS project (Montero et al., 2011), which are values per area of substrate culture system.

**Table 1.** Type of cultivation, productivity, water consumption and heating demand for Scenarios A, by study area.

| | **Spain** | **Portugal** | **The Netherlands** | **Germany** | **Colombia** | **Brazil** |
|---|---|---|---|---|---|---|
| **Scenario A** | | | | | | |
| Type of cultivation | Unheated greenhouse<br>Soil-less (substrate) | | Heated greenhouse<br>Soil-less (substrate) | | Unheated greenhouse<br>Soil-less (substrate) | |
| Productivity ($kg/m^2$) | 16.5(a) | 20.0(c) | 56.5(a) | 56.5(a) | 15.7(d) | 18.1(f) |
| Water consumption (L/kg) | 28.8(a) | 23.8(a*) | 14.06(a) | 14.06(a) | 22.5(e) | 26.4(g) |
| Heating demand ($MJ/m^2$) | 0(a) | 0(c) | 23.36(a) | 23.36(a) | 0(e) | 0(g) |
| Heating origin | - | - | Electricity mix (NL) | Electricity mix (DE) | - | - |

*(a)Data from EUPHOROS Project (Montero et al., 2011); (b)Data calculated using PrHo V. 2.0 (González et al., 2008); (b*)Adapted from PrHo V. 2.0; (c)Data from AGREE Project (Golaszewski and de Viser, 2012); (e)Jaramillo et al. (2007); (g)Burck Duarte et al. (2010).*

### (c) Cultivation parameters for isolated RTGs (Scenario B)

The implementation of integrated RTGs (Scenario B) considers that RTGs use the conventional greenhouse technology of the different study areas but by taking advantage of the introduction of the residual heat from the building into the greenhouse. This affects different depending on the geographic area:

- Warm climates: The residual heat introduced in the greenhouse is expected to increase the crop yield without enlarging the environmental impact (i.e., by consuming energy).
- Cold climates: The residual heat is expected to heat the greenhouse while substituting the current energy consumption for heating purposes.

The effect of the metabolic integration was analyzed as a sensitivity parameter. As a result, the effect on the crop was calculated from a 0% to 100% effect. The cultivation parameters for a 100% effect of the residual heat in the crop were obtained from literature data, adapted or calculated, as shown in Table 2. The application of fertilizers and pesticides are obtained from the EUPHOROS project (Montero et al. 2011), which are values per area of substrate culture system.

**Table 2.** Type of cultivation, productivity, water consumption and heating demand for Scenarios B, by study area.

| | Spain | Portugal | The Netherlands | Germany | Colombia | Brazil |
|---|---|---|---|---|---|---|
| **Scenario B** | | | | | | |
| Type of cultivation | Interconnected greenhouse with heating from residual heat<br>Soil-less (substrate) | | | | | |
| Productivity (kg/m$^2$) | 56.5(a) | 56.5(a) | 56.5(a) | 56.5(a) | 56.5(a) | 56.5(a) |
| Water consumption (L/kg) | 14.5(b) | 12.0(b*) | 14.06(a) | 14.06(a) | 14.5(b) | 14.5(b) |
| Heating demand (MJ/m$^2$) | 0(a) | 0(c) | 23.36(a) | 23.36(a) | 0(e) | 0(g) |
| Heating origin | Supplied by the residual heat from the building | | | | | |

*(a) Data from EUPHOROS Project (Montero et al., 2011); (b) Data calculated using PrHo V. 2.0 (González et al., 2008); (b*) Adapted from PrHo V. 2.0; (c) Data from AGREE Project (Golaszewski and de Viser, 2012); (e) Jaramillo et al. (2007); (g) Burck Duarte et al. (2010).*

### (d) Market considerations and quantification of the environmental benefits

The avoided energy and avoided CO$_2$ factors to quantify the benefits and the avoided impact factors for the different case studies were calculated following the methodology established in Sanyé-Mengual et al. (2013). This calculation method considers from the agricultural production to the retail stage. While the agricultural burdens were accounted as explained above, the adaptation of the data used for the distribution and retail stages were based on the tomato market, which determines the transportation distance, the packaging and the loss of product.

**Transportation distance** is obtained from market studies and research papers and corresponds to the current market for tomato in the study areas analyzed (Table 2).

**Table 2.** Market parameters considered for the comparison between conventional tomato production and potential RTG production.

| Study area | Study case | Origin for conventional production | Distance (km) | Source |
|---|---|---|---|---|
| Barcelona | Sant Boi | Almeria | 800 | Sanyé-Mengual et al. (2013) |
| | Montigalà | | | |
| Portugal | Lisbon | Ribatejo/Oeste | 70 | ESB/UCP (2001) |
| The Netherlands | Rotterdam | Westland Holland (Naaldwijk) | 30 | Breukers et al. (2008) |
| | Utrecht | Westland Holland (Naaldwijk) | 100 | |
| Deutschland | Berlin | Westland Holland (Naaldwijk) [68%]<br>Almeria [32%] | 1330<br>[average] | BLE (2013) |
| Brazil | Sao Carlos | Araraquara | 50 | Instituto de Economia Agrícola (2013) |
| Colombia | Manizales | Norte de Santander | 430 | Lopera Mesa et al. (2009) |

**Packaging:** In order to make the case studies comparable, the same packaging options were considered and were based on Sanyé-Mengual et al. (2013). For the conventional scenario a single-use plastic packaging (capacity of 6 kg) is considered, while the RTG scenarios assumes that the same packaging is re-used up to 50 times.

**Loss of product:** The loss of product considers the loss during transportation and in the retail stage. Transportation loss is the weight loss of the product due to refrigeration and is related to the transportation distance. Retail loss is related to the generation of waste food. According to data in Sanyé-Mengual et al. (2013) and Cerón-Palma et al., 2013), the formula for calculating the loss of product for each case study was determined as follows:

$$Loss\ of\ product\ (\%) = R_L + \left[7{,}5 \cdot 10^{-5} \cdot D \cdot (100 + R_L)\right]$$

***$7.5 \cdot 10^{-3}$*** *factor is obtained from Sanyé-Mengual et al. (2013) and is the ratio between loss of product (%) and transportation distance*

***D*** *= Transportation distance [km]*

$\boldsymbol{R_L}$ *= Retail loss – Retail loss was assumed 10% for European countries (according to results from Sanyé-Mengual et al., 2013) and 30% for American countries (as considered in Cerón-Palma et al., 2013)*

## Appendix 1.5: Correlation factors

The different outputs and indicators used in the study were assessed to observe the dependence to the input variables with the aim of answering the research question: "*What are the determining variables on RTGs outputs?*". The relation between outputs and variables was performed for the short-term potential, the production intensity, the total $CO_2$ savings, the self-sufficiency potential, the self-sufficiency area and the rainwater harvesting (RWH) improvement indicators (Table 1). Strong and moderate correlation results (values in bold in Table 1) are highlighted in the manuscript.

**Table.** Correlation between outputs and input variables, by type of parameter (design, RTG, production and others).

| | **Design** | | | | **RTG** | **Production** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Total area** | **Rooftop ratio** | **Type of roof** | **Roof material** | **Short-term potential** | **Crop yield** | **Production intensity** | **Impact factor** | **Consumption patterns** | **Rainfall pattern** |
| **Short-term potential** | **0.60** | 0.11 | **0.81** | 0.36 | | | | | | |
| **Production per area** | | 0.03 | | | **0.58** | **0.37** | | | | |
| **$CO_2$ savings** | | 0.01 | | | **0.70** | **0.60** | **0.42** | **0.56** | | |
| **Self-supply potential** | | 0.15 | | | 0.26 | 0.35 | **0.88** | | 0.17 | |
| **RWH improvement** | 0.1 | 0.23 | **0.97** | | **0.85** | | | | | 0.1 |

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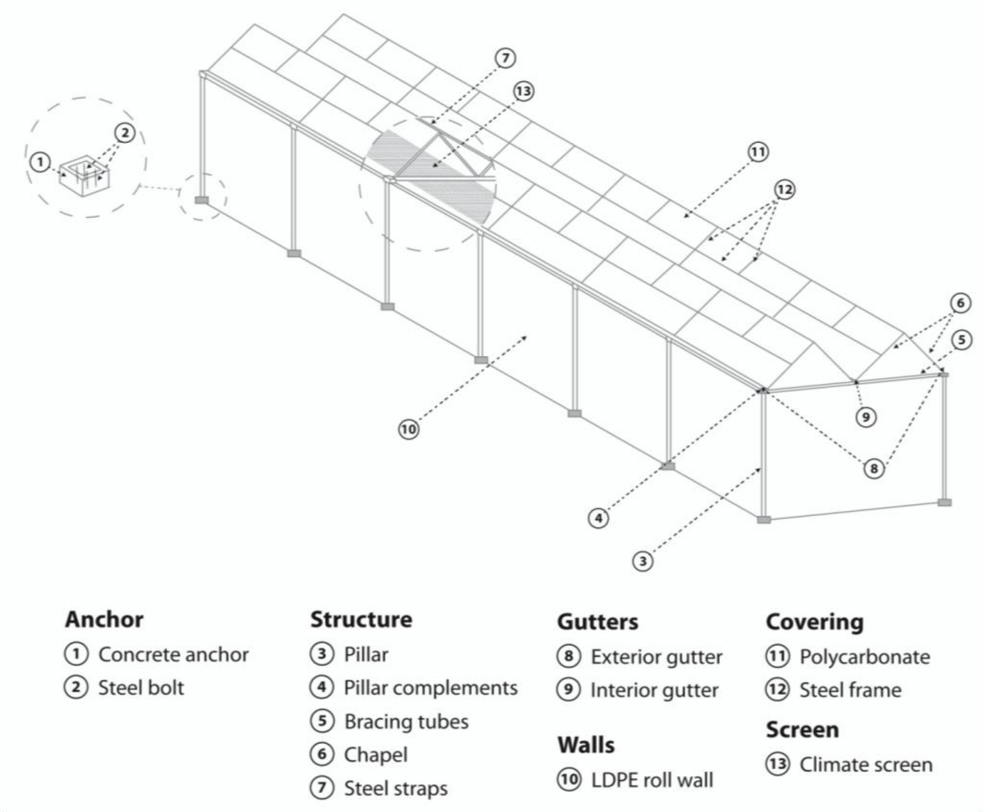
# Appendix 2. Supporting information for chapter 6.

Contents:

## Appendix 2.1: Detailed data of the RTG elements

The following table compiles data of the different rooftop greenhouse elements: material, lifespan and maintenance needs to fulfil building's lifespan (50 years). The lifespan of the element corresponds to producers' data and engineers' designs.



| Nº | Element | Material | Lifespan [y.] | Maintenance [nº changes] |
|---|---|---|---|---|
| | **Anchor** | | | |
| 1 | Concrete anchor | Concrete | 50 | - |
| 2 | Bolt | Steel (85% R) | 50 | - |
| | **Structure** | | | |
| 3 | Pillar | Steel (85% R) | 50 | - |
| 4 | Pillar complements | Steel (85% R) | 50 | - |
| 5 | Bracing tubes | Steel (85% R) | 50 | - |
| 6 | Chapel | Steel (85% R) | 50 | - |
| 7 | Straps | Steel (85% R) | 50 | - |
| | **Gutters** | | | |
| 8 | Exterior gutter | Steel (85% R) | 50 | - |
| 9 | Interior gutter | Steel (85% R) | 50 | - |
| | **Walls** | | | |
| 10 | Roll wall | 3-layer LDPE | 4 | 12.5 |
| | **Covering** | | | |
| 11 | Windows | Polycarbonate | 10 | 5 |
| 12 | Frame | Steel (85% R) | 50 | - |
| | **Climate screen** | | | |
| 13 | Climate screen | Polyester-Aluminium | 5 | 10 |

## Appendix 2.2: Life cycle inventory assumptions

*Materials transportation:* The transportation requirements of the materials were calculated according to the production site of each one. The following table compiles the origin, the distance, and the mode of transportation for each material of the RTG structure.

| Material | Origin | Distance (km) | Mode of transportation |
|---|---|---|---|
| Steel | Martorell, Spain | 77 | Lorry 16-32t, EURO5 |
| Polycarbonate | Doncaster, UK | 1008.44 | Transoceanic freight ship |
| | | 991.7 | Lorry 16-32t, EURO5 |
| Polyethylene | Tarragona, Spain | 101 | Lorry 16-32t, EURO5 |
| Concrete | Barcelona, Spain | 40 | Lorry 16-32t, EURO5 |
| Climate screen | Hellevoetsluis, The Netherlands | 1487 | Lorry 16-32t, EURO5 |

*Technical data of machinery used in the construction stage:* Two machineries were used in the construction of the rooftop greenhouse. On the one hand, a tower crane raised the materials and construction elements to the rooftop. On the other hand, the greenhouse was built by using a scissor platform. Both machineries are electric and their consumption was calculated based on the following technical specifications and on the weight of the amount of materials of the RTG.

| Characteristics | | Tower crane | Scissor platform |
|---|---|---|---|
| Brand, model | | Liebherr 90LD | Haulotte compact8 |
| Load capacity | | 1300 kg | 230 kg |
| Power | Rise | 22 kW | 4.44 kW |
| | Descent | 3.8 kW | 0.76 kW |
| Speed | Rise | 56 m/min | 41 s |
| | Descent | | 37 s |

## Appendix 2.3: Economic data adjustments

The economic costs were collected from different years, based on the available studies. However, 2013 was chosen as the reference year since the RTG was built in that period. To update costs from the collection year to the reference one, the present value was calculated for each cost according to the inflation rate.

The present value (PV) formula used for the calculations was:

$$PV = {C_i}^{(1+r)}$$

Where $C_i$ is the cost at the year $i$, and $r$ is the inflation rate value for the corresponding year.

The inflation rate for the period under assessment was obtained for Spain (IMF).

| Year | Year number (*i*) | Inflation rate (end of period) |
|---|---|---|
| 2008 | 0 | 1.455 |
| 2009 | 1 | 0.893 |
| 2010 | 2 | 2.861 |
| 2011 | 3 | 2.356 |
| 2012 | 4 | 2.998 |
| 2013 | 5 | 0.305 |

The collection year for the costs related to each stage and system are listed below.

| Value | RTG system | Multitunnel system |
|---|---|---|
| Greenhouse structure cost | 2013 | 2008 |
| Crop inputs cost | 2008 | 2008 |
| Electricity cost | 2013 | 2013 |
| Packaging cost | 2011 | 2011 |
| Distribution transportation cost | 2012 | 2012 |
| Tomato producer price (Euphoros) | 2008 | 2008 |
| Tomato wholesale price | 2009 | 2009 |
| Tomato consumer price | 2013 | 2013 |

## Appendix 2.4: Life cycle inventory and economic costs of the greenhouse structures of an RTG and a multitunnel greenhouse

**Life cycle inventory:** The following table displays the life cycle inventory of the greenhouse structure of the RTG on the ICTA-ICP building and the multi-tunnel greenhouse structure in Almeria. RTG data is obtained from the architectural project, or calculated. Multitunnel data is entirely obtained from the Euphoros project (Montero et al. 2011), which included the maintenance requirements in the materials stage. The LCI refers to the functional unit of 1 $m^2$ of a greenhouse structure for a timeframe of 1 year.

| Life cycle stage | Input | Unit | RTG<br>Per $m^2$ | Source | Multitunnel<br>Per $m^2$ |
|---|---|---|---|---|---|
| Materials | Steel (100% recycled) | kg | 0.836 | Project data | 0.513 |
| | Concrete | kg | 0.212 | Project data | 0.505 |
| | LDPE | kg | 0.006 | Project data | 0.159 |
| | Polycarbonate | kg | 0.032 | Project data | 0.011 |
| | Polyester | kg | 0.0008 | Project data | - |
| | Aluminium | kg | 0.0008 | Project data | - |
| | Polypropylene | kg | - | - | 0,021 |
| | PVC | kg | - | - | 0,012 |
| | Lorry 35-40t EURO5 | tkm | 0.124 | Calculation | 0.438 |
| | Transoceanic freight ship | tkm | 0.032 | Calculation | - |
| Construction | Machinery use | kWh | 0.0004 | Calculated | - |
| Maintenance | LDPE | kg | 0.072 | Project data | - |
| | Polycarbonate | kg | 0.128 | Project data | - |
| | Polyester | kg | 0.007 | Project data | - |
| | Aluminium | kg | 0.007 | Project data | - |
| | Lorry 35-40t EURO5 | tkm | 0.154 | Calculation | - |
| | Transoceanic freight ship | tkm | 0.129 | Calculation | - |
| End of life | Recycling process | kg | 1.302 | Project data | 1,188 |
| | Transport, lorry 16-32t | tkm | 0.046 | Calculated | - |

**Economic costs:** The following table compiles the economic costs of the Rooftop Greenhouse of the RTG-Lab according to project data. For materials, cost data is cradle-to-construction site, including: material extraction, material processing, labour, and transportation. Data corresponds to the functional unit of 1m$^2$ and 1 year. Regarding the multi-tunnel greenhouse, the EUPHOROS project (Montero et al. 2011) only showed the global costs of the infrastructure: 3.84€·m$^{-2}$·year$^{-1}$.

| **Life cycle stage** | **Input** | **RTG [€/m$^2$]** |
|---|---|---:|
| Materials | Steel | 3.12 |
| | Concrete | 0.005 |
| | LDPE | 0.26 |
| | Polycarbonate | 1.06 |
| | Climate screen | 0.56 |
| Construction | Machinery use | 0.00 |
| | Labour | 0.324 |
| Maintenance | LDPE | 0.39 |
| | Polycarbonate | 1.06 |
| | Climate screen | 5.05 |
| Waste management | Transport, lorry 16-32t | 0.006 |
| **TOTAL COST** | | **11.9** |

## Appendix 2.5: Life cycle inventory and economic costs of the tomato production in an RTG in Bellaterra and a multitunnel greenhouse in Barcelona

**Life cycle inventory:** The following table displays the life cycle inventory of the tomato production in the RTG of the ICTA-ICP building (Bellaterra) and a multi-tunnel greenhouse structure in Almeria. RTG data is obtained from the architectural project, adapted from the Euphoros project (Montero et al. 2011), or calculated. Multitunnel data is entirely obtained from the Euphoros project (Montero et al. 2011).

| Input | | RTG | | | Multitunnel | |
|---|---|---|---|---|---|---|
| | Unit | Per m$^2$ | Per kg | Source | Per m$^2$ | Per kg |
| **Greenhouse structure** | | | | | | |
| Steel (100% recycled) | kg | 8,36E-01 | 3,34E-02 | Project data | 5,13E-01 | 3,11E-02 |
| Concrete | kg | 2,12E-01 | 8,48E-03 | Project data | 5,05E-01 | 3,06E-02 |
| LDPE | kg | 7,80E-02 | 3,12E-03 | Project data | 1,59E-01 | 9,64E-03 |
| Polycarbonate | kg | 1,60E-01 | 6,40E-03 | Project data | 1,10E-02 | 6,67E-04 |
| Polyester | kg | 7,80E-03 | 3,12E-04 | Project data | - | - |
| Aluminium | kg | 7,80E-03 | 3,12E-04 | Project data | - | - |
| PVC | Kg | - | - | - | 1,20E-02 | 7,27E-04 |
| Lorry 35-40t EURO5 | tkm | 2,78E-01 | 1,11E-02 | Calculation | 4,38E-01 | 2,65E-02 |
| Transoceanic freight ship | tkm | 1,61E-01 | 6,44E-03 | Calculation | - | - |
| Machinery use | kWh | 4,00E-04 | 1,60E-05 | Calculation | - | - |
| Lorry 35-40t EURO5 | tkm | 1,30E+00 | 5,21E-02 | Calculation | - | - |
| Recycling process | kg | 4,60E-02 | 1,84E-03 | Project data | - | - |
| **Auxiliary equipment** | | | | | | |
| LDPE | kg | 2,30E-02 | 9,20E-04 | Montero | 2,30E-02 | 1,39E-03 |
| Polystyrene | kg | 2,60E-02 | 1,04E-03 | et al. (2011) | 2,60E-02 | 1,58E-03 |
| HDPE | kg | 9,40E-03 | 3,76E-04 | | 9,40E-03 | 5,70E-04 |
| PVC | kg | 4,40E-03 | 1,76E-04 | | 4,40E-03 | 2,67E-04 |
| Steel (100% recycled) | kg | 5,00E-04 | 2,00E-05 | | 5,00E-04 | 3,03E-05 |
| Expanded perlite | kg | 6,20E-01 | 2,48E-02 | | 6,20E-01 | 3,76E-02 |
| Van, <3.5t | tkm | 2,00E-04 | 8,00E-06 | | 2,00E-04 | 1,21E-05 |
| **Inputs consumption** | | | | | | |
| Water (rainwater) | $m^3$ | 7,97E-01 | 3,19E-02 | Calculated | - | |
| Water (groundwater) | $m^3$ | | | | 4,74E-01 | 2,87E-02 |
| Electricity | kWh | 1,08E+00 | 4,32E-02 | Adapt. | 6,36E-01 | 3,85E-02 |
| Fertilizer (N) | g | 9,76E+02 | 3,90E+01 | Montero | 7,99E+02 | 4,84E+01 |
| Fertilizer ($P_2O_5$) | g | 6,18E+01 | 2,47E+00 | et al. (2011) | 5,06E+01 | 3,06E+00 |
| Fertilizer ($K_2O$) | g | 1,91E+01 | 7,64E-01 | | 1,56E+01 | 9,47E-01 |
| Pesticides | g | 4,00E+00 | 1,60E-01 | | 3,27E+00 | 1,98E-01 |
| **Waste management** | | | | | | |
| Recycling process | kg | 6,83E-01 | 2,73E-02 | Calculated | 3,41E-01 | 2,07E-02 |
| Final disposal | kg | - | - | - | 3,42E-01 | 2,07E-02 |
| Transport, van <3.5t | tkm | 1,32E-01 | 5,28E-03 | Calculated | 2,20E-02 | 1,33E-03 |
| Transport, lorry 7.5t | tkm | - | - | - | 5,00E-03 | 3,03E-04 |

**Economic costs:** The following table shows the economic costs related to the tomato production in an RTG (Bellaterra) and in a multi-tunnel greenhouse (Almeria). Results are shown per area and per kg of product. Multitunnel data is entirely obtained from the Euphoros project (Montero et al. 2011).

| **Input** | **RTG** | | | **Multitunnel** | |
|---|---|---|---|---|---|
| | **Per $m^2$** | **Per kg** | **Source** | **Per $m^2$** | **Per kg** |
| Greenhouse structure | 11,9 | 0,476 | Project | 4,26 | 0,258 |
| Auxiliary equipment | 1,51 | 0,0604 | Montero et al. (2011) | 1,51 | 0,092 |
| Water | 0 | 0 | Calculated | 0,222 | 0,013 |
| Electricity | 0,391 | 0,01564 | Adapted from Montero et al. (2011) | 0,233 | 0,014 |
| Fertilizers | 0,814 | 0,03256 | | 0,666 | 0,040 |
| Pesticides | 0,475 | 0,019 | | 0,389 | 0,024 |
| Paid labour | 3,337 | 0,13348 | | 2,731 | 0,166 |
| **TOTAL COST** | **18.43** | **0.737** | | **10.01** | **0.607** |

## Appendix 2.6: Life cycle inventory of the tomato production in an RTG in Bellaterra and a multitunnel greenhouse in Barcelona

The following table displays the life cycle inventory of the local supply-chain of tomatoes produced in an RTG in Bellaterra and consumed in Barcelona, and of the industrial supply-chain of tomatoes produced in a multi-tunnel greenhouse in Almeria and consumed in Barcelona. The functional unit of the inventory is 1 kg of tomato at the consumer. The inventory of the multi-tunnel system is based on Sanyé-Mengual et al. (2013).

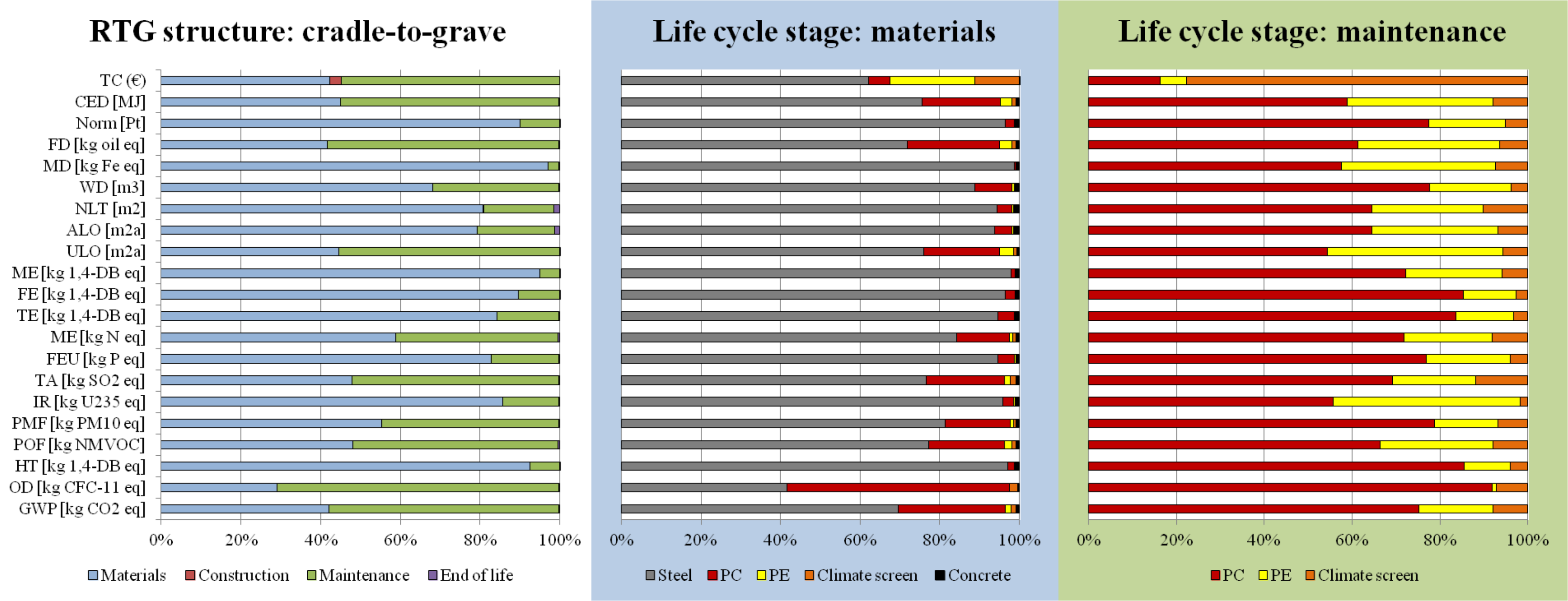
| Life cycle stage | Input | Unit | RTG | Multi-tunnel |
|---|---|---|---|---|
| Agriculture production | Tomato produced | kg | 1 | 1.166 |
| Packaging production | HDPE tray | kg | 0.1 | 0.1166 |
| Distribution | Transportation, lorry 5t | km | - | 20 |
| | Transportation, lorry 45t | km | - | 825 |
| | Distribution centre | kWh | - | $0.743 \cdot 10^{-3}$ |
| | Transportation, van 3.5t | km | 25 | 10 |
| Retail | Loss of product | kg | 0 | 0.1 |

**Economic costs:** The following table compiles the costs of the supply-chain of tomatoes in the RTG and the multi-tunnel scenario.

| Life cycle stage | Input | RTG [€] | Multi-tunnel [€] |
|---|---|---|---|
| Agriculture production | Tomato produced | 0.752 | 0.643 |
| Packaging production | HDPE tray | 0.105 | 0.119 |
| Distribution | Transportation, lorry 5t | - | 0.005 |
| | Transportation, lorry 45t | - | 0.0644 |
| | Distribution centre | - | 0.001 |
| | Transportation, van 3.5t | 0.006 | 0.003 |
| Retail | Loss of product | - | 0.147 |
| **TOTAL** | | **0.863** | **0.982** |

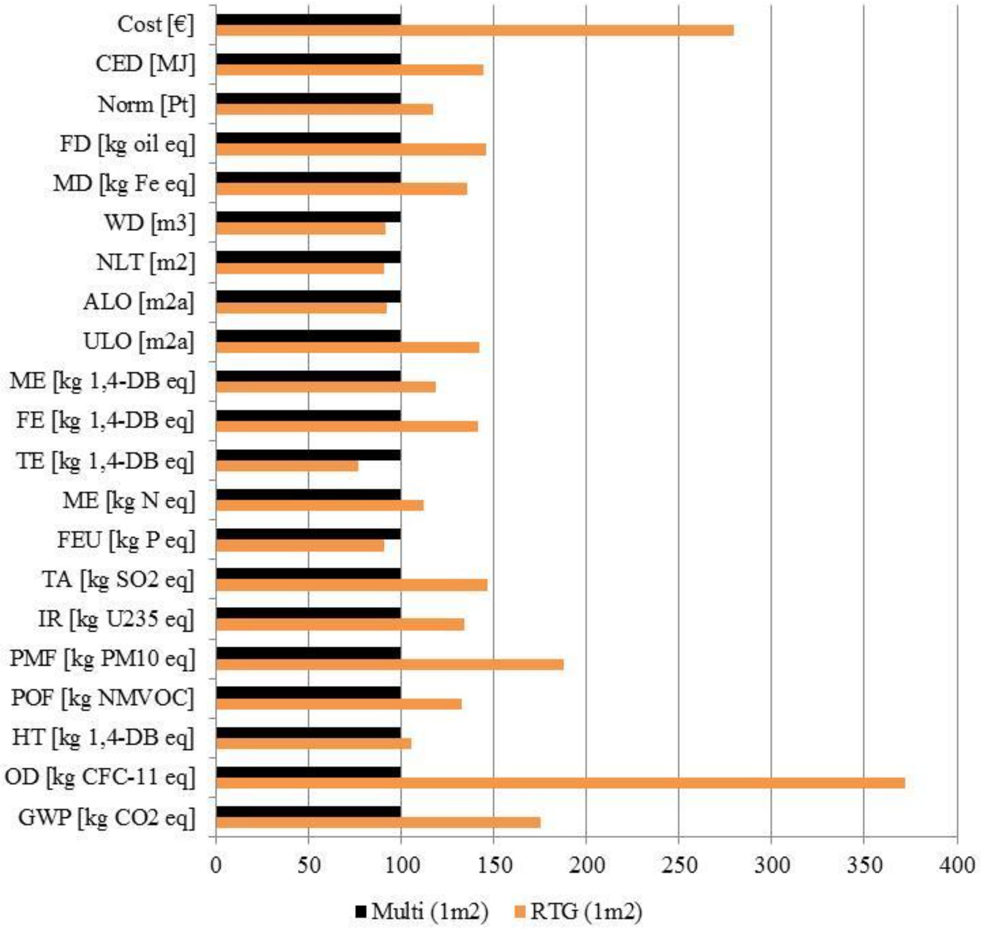
## Appendix 2.7: Life cycle impact assessment results for the RTG structure and comparison to multi-tunnel results

The following figure details the distribution of the environmental burdens of 1 m$^2$ of the RTG structure for a timeframe of 1 year. The contribution of the different life cycle stages is shown in the cradle-to-grave figure, while the contribution of the materials is reported for the materials [blue graph] and for the maintenance [green graph] life cycle stages.



**Global Warming Potential (GWP), Ozone depletion (OD), Human toxicity (HT), Photochemical oxidant formation (POF), Particulate matter formation (PMF), Ionising radiation (IR), Terrestrial acidification (TA), Freshwater eutrophication (FE), Marine eutrophication (ME), Terrestrial ecotoxicity (TE), Freshwater ecotoxicity (FE), Marine ecotoxicity (ME), Agricultural land occupation (ALO), Urban land occupation (ULO), Natural land transformation (NLT), Water depletion (WD), Metal depletion (MD), Fossil depletion (FD), Normalized-ReCiPe (Norm), Cumulative Energy Demand (CED), and Cost.*

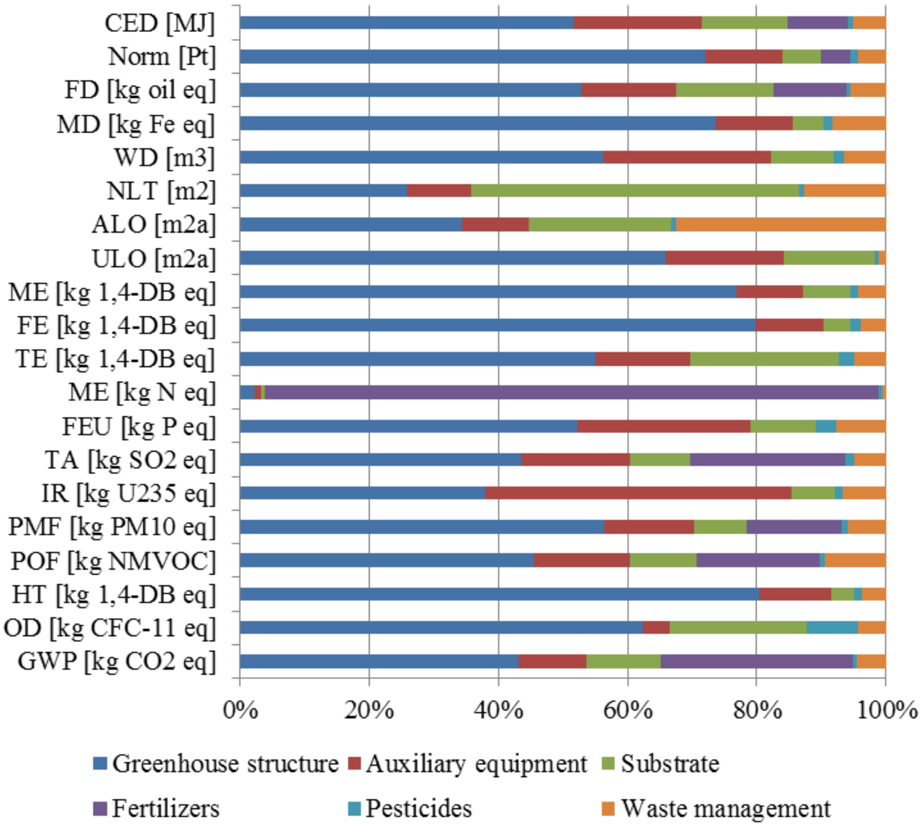
**Comparison to multi-tunnel results:** The environmental impact and economic cost of the RTG structured is compared to a multi-tunnel greenhouse structure by showing the relative values per 1 m$^2$.



**Global Warming Potential (GWP), Ozone depletion (OD), Human toxicity (HT), Photochemical oxidant formation (POF), Particulate matter formation (PMF), Ionising radiation (IR), Terrestrial acidification (TA), Freshwater eutrophication (FE), Marine eutrophication (ME), Terrestrial ecotoxicity (TE), Freshwater ecotoxicity (FE), Marine ecotoxicity (ME), Agricultural land occupation (ALO), Urban land occupation (ULO), Natural land transformation (NLT), Water depletion (WD), Metal depletion (MD), Fossil depletion (FD), Normalized-ReCiPe (Norm), Cumulative Energy Demand (CED), and Cost.*

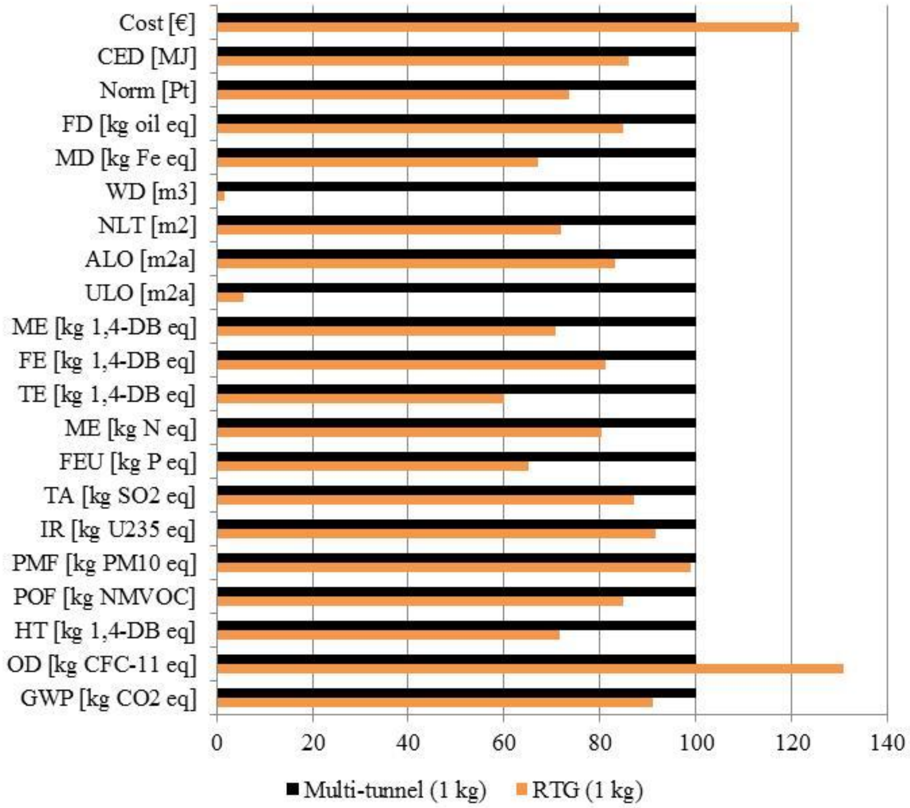
## Appendix 2.8: Environmental results for tomato production in RTG and comparison to multi-tunnel results

**Distribution of the environmental impact of 1 kg produced in an RTG at the farm gate.** The chart shows the distribution of the environmental impact among life cycle stages of the different environmental indicators of the ReCiPe method, the normalized value and the CED.



**Global Warming Potential (GWP), Ozone depletion (OD), Human toxicity (HT), Photochemical oxidant formation (POF), Particulate matter formation (PMF), Ionising radiation (IR), Terrestrial acidification (TA), Freshwater eutrophication (FE), Marine eutrophication (ME), Terrestrial ecotoxicity (TE), Freshwater ecotoxicity (FE), Marine ecotoxicity (ME), Agricultural land occupation (ALO), Urban land occupation (ULO), Natural land transformation (NLT), Water depletion (WD), Metal depletion (MD), Fossil depletion (FD), Normalized-ReCiPe (Norm), Cumulative Energy Demand (CED), and Cost.*

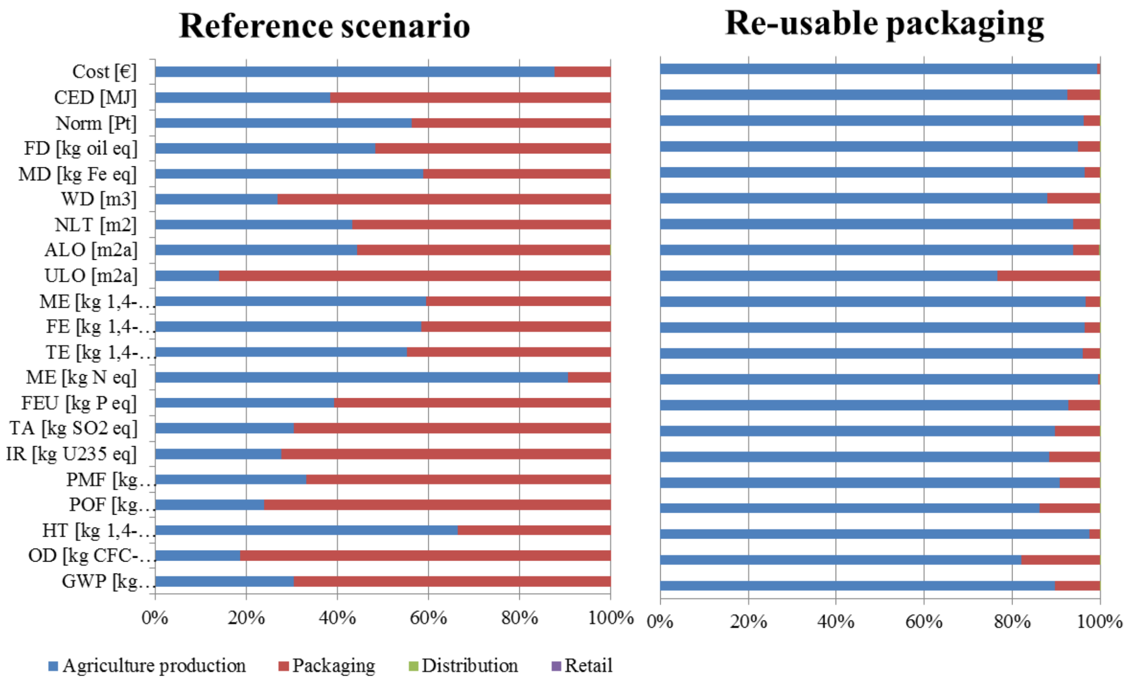
**Comparison to multi-tunnel results:** The environmental impact and economic cost of the RTG structured is compared to a multi-tunnel greenhouse structure by showing the relative values per 1 kg of tomato produced.



**Global Warming Potential (GWP), Ozone depletion (OD), Human toxicity (HT), Photochemical oxidant formation (POF), Particulate matter formation (PMF), Ionising radiation (IR), Terrestrial acidification (TA), Freshwater eutrophication (FE), Marine eutrophication (ME), Terrestrial ecotoxicity (TE), Freshwater ecotoxicity (FE), Marine ecotoxicity (ME), Agricultural land occupation (ALO), Urban land occupation (ULO), Natural land transformation (NLT), Water depletion (WD), Metal depletion (MD), Fossil depletion (FD), Normalized-ReCiPe (Norm), Cumulative Energy Demand (CED), and Cost.*

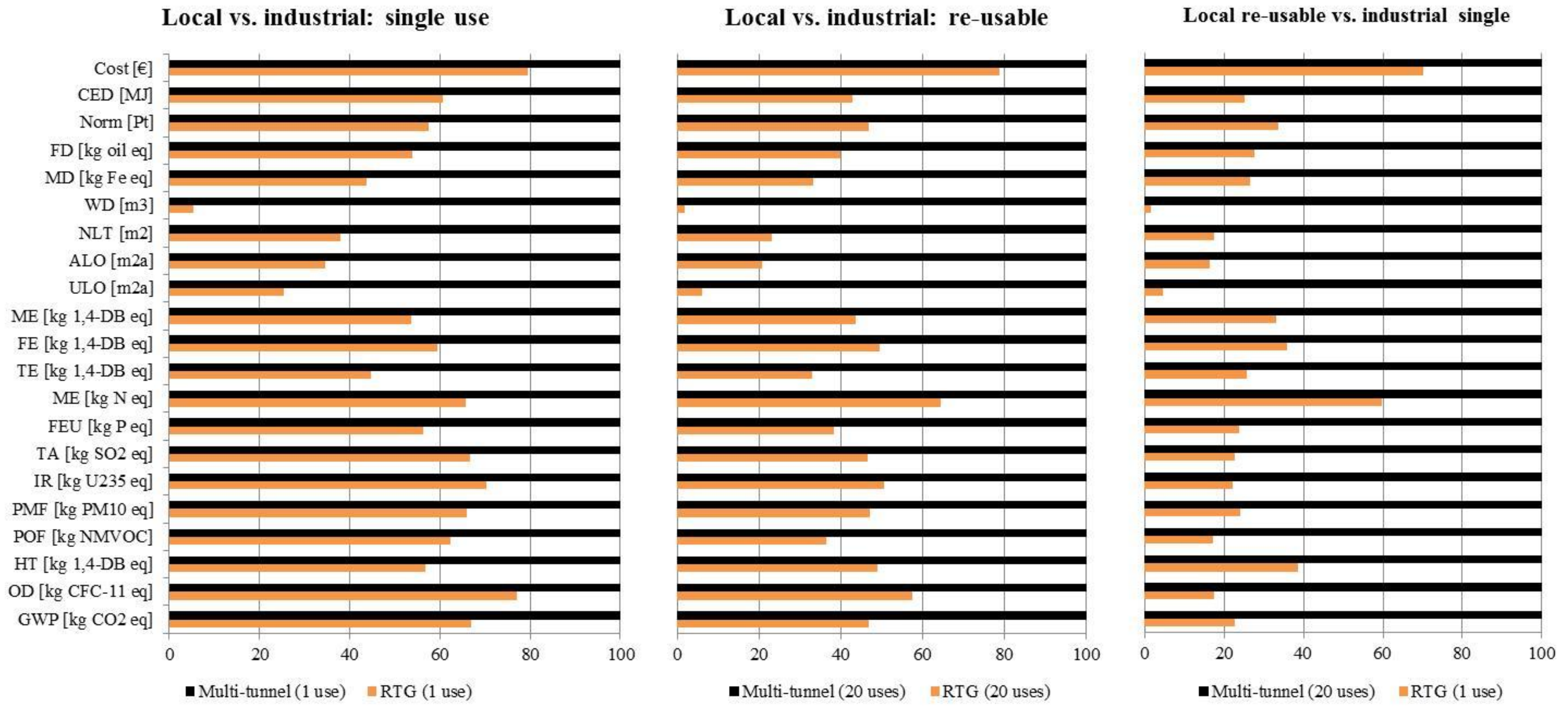
## Appendix 2.9: Environmental and economic assessment of tomato supply-chains: local supply-chain from RTGs, and industrial supply-chain from multi-tunnel

The following chart shows the distribution of the environmental impact and the economic cost among the life cycle stages of the RTG local supply chain of tomato. The reference scenario considers that the packaging is a single-use product. However, a second scenario was analyzed to show the sensitivity of the results regarding the intensity of use of the packaging of the product. The “re-usable packaging” scenario considers that the packaging can be re-used up to 20 times, assuming that a local supply-chain is a more controlled system as discussed in Sanyé-Mengual et al. (2013).



**Global Warming Potential (GWP), Ozone depletion (OD), Human toxicity (HT), Photochemical oxidant formation (POF), Particulate matter formation (PMF), Ionising radiation (IR), Terrestrial acidification (TA), Freshwater eutrophication (FE), Marine eutrophication (ME), Terrestrial ecotoxicity (TE), Freshwater ecotoxicity (FE), Marine ecotoxicity (ME), Agricultural land occupation (ALO), Urban land occupation (ULO), Natural land transformation (NLT), Water depletion (WD), Metal depletion (MD), Fossil depletion (FD), Normalized-ReCiPe (Norm), Cumulative Energy Demand (CED), and Cost.*

The two RTG scenarios are compared to the industrial supply-chain in the following figure: comparison of single-use packaging scenarios, comparison of re-usable packaging scenarios, and comparison of local supply-chain with re-usable packaging with industrial supply-chain with single-use packaging.



**Global Warming Potential (GWP), Ozone depletion (OD), Human toxicity (HT), Photochemical oxidant formation (POF), Particulate matter formation (PMF), Ionising radiation (IR), Terrestrial acidification (TA), Freshwater eutrophication (FE), Marine eutrophication (ME), Terrestrial ecotoxicity (TE), Freshwater ecotoxicity (FE), Marine ecotoxicity (ME), Agricultural land occupation (ALO), Urban land occupation (ULO), Natural land transformation (NLT), Water depletion (WD), Metal depletion (MD), Fossil depletion (FD), Normalized-ReCiPe (Norm), Cumulative Energy Demand (CED), and Cost.*

## Appendix 2.10: Sensitivity analysis of minimum tomato price to cover RTG production costs, by crop yield.

RTG businesses can sell their product in different ways, as observed in current experiences: Gotham Greens sell their products in supermarkets, Lufa Farms distribute the horticultural products through a Community Supported Agriculture (CSA) model, and The Vinegar Factory built the RTG on the top of its own specialized shop, where the products are sold. Therefore, there are two common pathways for the end-consumer to purchase RTG products. First, the RTG company can sell them directly, taking advantage of the avoided distribution and retail costs. Second, the RTG company can sell the produce to an intermediary agent, who puts it on sale.

According to economic studies of the tomato supply chain, there are three prices:

- The price of tomato sold by the producer: 0.610 €/kg (2013) (updated price from the study of the tomato production in a multitunnel greenhouse in Almeria, 0,578 €/kg (Montero et al. 2011))
- The price of tomato sold by wholesale agents: 1.176 €/kg (2013) (updated price from the study of the value chain and price formation of tomato, 1.075 €/kg (MAGRAMA 2009))
- The price of tomato sold by retailers: 1.475 €/kg (2013) (according to the food consumption statistics at the Catalan level (MAGRAMA 2014))

Since production costs strongly depend on the crop yield, a sensitivity analysis was performed. The minimum tomato price is calculated according to the production costs and a profit margin rate of 6%, according to data from the multitunnel production system (Montero et al. 2011). The resulting minimum tomato prices are compared to the producer tomato price, the wholesale tomato price, and the retail tomato price.

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# Appendix 3. Supporting information for chapter 9

Contents:

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**Appendix 3.4.** Recipe midpoint indicators for the crops under assessment.

**Appendix 3.1.** Review of LCA studies that compare local and imported food products.

| Area | Scope | Conventional case | Main results/VALUES | Methods | Study |
|---|---|---|---|---|---|
| UK (Brixton, Denbigh) | Comparison of UK apple production (local farms and home-grown) and imported apples (international and regional) | MULTIPLE CASES<br>Minimum and maximum distances are covered. | Distribution of apples can vary from<br>0 MJ (home-grown, LP) to 17.75MJ (CP) | **LCA**<br>Direct energy<br>consumption<br>$CO_2$ emissions | (Jones 2002) |
| Germany | Comparison of apple production in<br>Germany and production in New Zealand | SINGLE CASE<br>New Zealand has the largest market share of imported apples | Local produced apples are 20% less energy-intensive than imported ones<br>Consumer shopping and cultivation are the more impacting stages in local systems | **LCA**<br>Primary energy use | (Blanke and Burdick 2005) |
| UK | Comparison of local apples and apples<br>sourced from Chile, Brazil or Italy<br>Comparison of local beans and beans<br>sourced from Kenya or Guatemala | MULTIPLE CASES<br>Conventional supply-chains are based on retailer data (Marks and Spencer's). Market shares are not shown | Apple storage in UK resulted less impacting than importation from the Southern hemisphere<br>Importation from Europe (Italy) was the best option, apart from eutrophication<br>Local beans can be up to 20-26 times less impacting than imported beans | **LCA**<br>CML 2 Baseline | (Sim et al. 2006) |
| UK | Comparison of UK apple production in and production in Europe and New Zealand | SINGLE CASE<br>Market shares are not shown | Energy consumption of domestic and<br>imported apples depend on the season and<br>the supply-chain (storage) | **LCA**<br>Primary energy use | (Milà i Canals et al. 2007) |
| UK | Comparison of local small-scale<br>systems and large-scale system of<br>different vegetables | MULTIPLE CASES<br>Retailer data (Riverford): 15% UK food and 15% overseas food. | Food-miles may include customer<br>transportation<br>Impacts of the supply-chain are covered<br>up for customer distances larger than 7.4km | **Food-miles**<br>Embedded energy<br>$CO_2$ emissions | (Coley et al. 2009) |
| Barcelona (Spain) | Comparison of local tomatoes from<br>Rooftop Greenhouses and conventional<br>tomatoes produced in unheated | SINGLE CASE<br>Almeria represents 60% of the tomato market in Barcelona | Local tomatoes could be between 44 and 75% less impacting than conventional ones.<br>The decrease in transport, packaging and | **LCA**<br>CED<br>CML 2 | (Sanyé-Mengual et al. 2013) |

| | | | | | |
|---|---|---|---|---|---|
| | greenhouses in Almeria (Spain) | | food losses are main issues | baseline | |
| Barcelona (Spain) | Compare of the local supply-chain of tomatoes of the Rooftop Greenhouse Lab (Bellaterra) and the imported supply-chain of tomatoes from Almería | SINGLE CASE<br>Almeria represents 60% of the tomato market in Barcelona | Local supply-chain is less impacting than the imported supply-chain, although to be cheaper local products may substitute imported products from farther than 400km | **LCA**<br>ReCiPe<br>CED<br>**LCC** (CBA) | (Sanyé-Mengual et al. 2015) |
| UK | Comparison of imported and locally produced apples, cherries, strawberries, garlic and peas | MULTIPLE CASES<br>National-scale market share. | An increase in the local production would lead to the substitution of current imported commodities and a significant reduction of food carbon emissions. | **Carbon emissions** | (Michalský and Hooda 2015) |
| France | Comparison of local off-season tomatoes and imported tomatoes from Morocco | SINGLE CASE<br>Morocco was chosen as an agricultural area with water scarcity issues. French market shares are not shown. | Off-season tomatoes from French producers have a larger environmental impact in some categories than Moroccan tomatoes. However, water deprivation in Moroccan production is more than 3 times higher, creating a trade-off among indicators. | **LCA**<br>Climate change<br>Non-renewable energy consumption<br>Eutrophication<br>Acidification<br>Water deprivation | (Payen et al. 2015) |

**Appendix 3.2.** LCI of the auxiliary equipment of the private rooftop garden for a functional unit of 1m$^2$ and a timeframe of 1 year.

| | | Lifespan | Amount | Unit |
|---|---|---|---|---|
| **Structure** | | | | |
| Wood | Sawnwood | 10 | 0.063 | m3 |
| Waterproof | Poliester | 10 | 0.012 | kg |
| **Growing system** | | | | |
| Tray | Expanded polystyrene (EPS) | 3 | 0.145 | kg |
| Perlite | Perlite | 3 | 2.093 | kg |
| Packaging (perlite) | LDPE | 3 | 0.031 | kg |
| Packaging (tray) | LDPE | 3 | 0.002 | kg |
| **Fertirrigation** | | | | |
| Drippers | Polypropylene (PP) | 5 | 0.001 | kg |
| Tube | Polyethylene (HDPE) | 3 | 0.028 | kg |
| Tube | HDPE | 3 | 0.024 | kg |
| Supporting stake | PP | 5 | 0.002 | kg |
| Microtube | Polyvinylchloride (PVC) | 10 | 0.003 | kg |
| Tank | PVC | 10 | 0.036 | kg |
| Tubes, connections | PVC | 10 | 0.016 | kg |
| Timer, injectors | PP | 10 | 0.013 | kg |
| Manometer | Steel | 10 | 0.002 | kg |
| Filters, stoppers | HDPE | 3 | 0.025 | kg |
| **Waste management** | | | | |
| Transport (kgkm) | | | 72.592 | kgkm |
| Waste to recycle | | | 2.420 | kgkm |

**Appendix 3.3.** Fertirrigation: Composition of nutrient solution (1L).

| Component | Formula | Amount [kg] |
|---|---|---|
| Tapwater | - | 1 |
| Nitric acid | $HNO_3$ | 0.0032 |
| Monopotassium phosphate | $KPO_4H_2$ | 0.0136 |
| Potassium sulfide | $K_2SO_4$ | 0.0261 |
| Potassium nitrate | $KNO_3$ | 0.0303 |
| Calcium nitrate | $Ca(NO_3)$ | 0.0328 |
| Calcium chloride | $CaCl_2$ | 0.0111 |
| Magnesium nitrate | $Mg(NO_3)$ | 0.0222 |
| *Hortilene* | - | 0.001 |
| *Sequestrene* | - | 0.001 |

**Appendix 3.4.** Recipe midpoint indicators for the crops under assessment.

| | | Tomato | Lettuce (1) | Lettuce (2) | Lettuce (3) | Beet | Chard | Cabbage |
|---|---|---|---|---|---|---|---|---|
| GW | kg $CO_2$ eq | 1,78E-01 | 2,45E-01 | 4,94E-01 | 4,59E+00 | 1,79E-01 | 8,60E-01 | 2,45E+00 |
| OD | kg CFC-11 eq | 7,79E-08 | 1,20E-07 | 2,03E-07 | 2,23E-06 | 7,34E-08 | 4,12E-07 | 1,19E-06 |
| TA | kg SO2 eq | 8,93E-04 | 1,24E-03 | 2,47E-03 | 2,32E-02 | 8,95E-04 | 4,34E-03 | 1,24E-02 |
| FEU | kg P eq | 3,52E-05 | 4,77E-05 | 9,85E-05 | 8,94E-04 | 3,57E-05 | 1,68E-04 | 4,77E-04 |
| MEU | kg N eq | 1,12E-03 | 1,75E-03 | 2,90E-03 | 3,24E-02 | 1,05E-03 | 5,97E-03 | 1,73E-02 |
| HT | kg 1,4-DB eq | 5,44E-02 | 7,41E-02 | 1,52E-01 | 1,39E+00 | 5,51E-02 | 2,61E-01 | 7,40E-01 |
| POF | kg NMVOC | 9,44E-04 | 1,40E-03 | 2,51E-03 | 2,61E-02 | 9,11E-04 | 4,84E-03 | 1,39E-02 |
| PMF | kg PM10 eq | 3,50E-04 | 4,97E-04 | 9,55E-04 | 9,29E-03 | 3,46E-04 | 1,73E-03 | 4,95E-03 |
| TE | kg 1,4-DB eq | 4,94E-05 | 7,51E-05 | 1,30E-04 | 1,39E-03 | 4,70E-05 | 2,58E-04 | 7,44E-04 |
| FE | kg 1,4-DB eq | 2,63E-03 | 3,68E-03 | 7,23E-03 | 6,88E-02 | 2,62E-03 | 1,29E-02 | 3,67E-02 |
| ME | kg 1,4-DB eq | 2,49E-03 | 3,48E-03 | 6,85E-03 | 6,51E-02 | 2,48E-03 | 1,22E-02 | 3,47E-02 |
| IR | kBq U235 eq | 2,65E-02 | 3,89E-02 | 7,09E-02 | 7,24E-01 | 2,57E-02 | 1,34E-01 | 3,86E-01 |
| ALO | m$^2$a | 2,60E+00 | 4,10E+00 | 6,67E+00 | 7,59E+01 | 2,42E+00 | 1,40E+01 | 4,05E+01 |
| ULT | m$^2$a | 2,64E-02 | 4,12E-02 | 6,82E-02 | 7,63E-01 | 2,47E-02 | 1,40E-01 | 4,07E-01 |
| NLT | m$^2$ | 6,91E-05 | 1,05E-04 | 1,81E-04 | 1,95E-03 | 6,58E-05 | 3,61E-04 | 1,04E-03 |
| WD | m$^3$ | 1,65E-02 | 1,82E-02 | 5,07E-02 | 3,47E-01 | 1,84E-02 | 6,74E-02 | 1,85E-01 |
| MD | kg Fe eq | 1,57E-02 | 2,19E-02 | 4,35E-02 | 4,09E-01 | 1,58E-02 | 7,65E-02 | 2,18E-01 |
| FD | kg oil eq | 4,90E-02 | 7,14E-02 | 1,32E-01 | 1,33E+00 | 4,78E-02 | 2,47E-01 | 7,09E-01 |

**Global Warming Potential (GW), Ozone depletion (OD), Human toxicity (HT), Photochemical oxidant formation (POF), Particulate matter formation (PMF), Ionising radiation (IR), Terrestrial acidification (TA), Freshwater eutrophication (FE), Marine eutrophication (ME), Terrestrial ecotoxicity (TE), Freshwater ecotoxicity (FE), Marine ecotoxicity (ME), Agricultural land occupation (ALO), Urban land occupation (ULO), Natural land transformation (NLT), Water depletion (WD), Metal depletion (MD) and Fossil depletion (FD).*

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