Universitat Autònoma de Barcelona

Assessing building's rooftop potential to integrate food, water, and energy systems: The use of remote sensing technology and perceptual aspects in a Mediterranean region

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Doctoral thesis

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Nothing ever goes away until it has taught us what we need to know.

Pema Chodron

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List of abbreviations and acronyms

AISA	Airborne Imaging System for different Applications
ASD	Analytical Spectral Devices
ASTER	Advanced Spaceborne Thermal Emission and Reflection
AVIRIS	Airborne Visual and Infra Red Imaging Spectrometer
CASI	Compact Airborne Spectral Imager
CO_2	Carbon Dioxide
DEMs	Digital Elevation Models
DNs	Digital Numbers
DSMs	Digital Surface Models
EC	Errors of Commission
EO	Errors of Omission
FWE	Food, Water, and Energy
GHG	Greenhouse Gas
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GR	Green Roof
HSR	High Spatial Resolution
ICGC	Institut Cartogràfic i Geològic de Catalunya
ICTA	Environmental Science and Technology Institute
IFOV	Instantaneous Field Of View
LiDAR	Light Detection and Ranging
LWIR	Long Wave Infrared
NCEP	National Centers for Environmental Prediction
NIR	Near infrared
NYC	New York City
OA	Overall Accuracy
OU	Owners and Users
PA	Producer's Accuracy
PA	Public Administrations
PC	Private Companies
PV	Photovoltaic
RS	Remote Sensor
RTG	Rooftop Greenhouse

RTGs	Rooftop Greenhouses
RUA	Rooftop Urban Agriculture
RWHS	Rainwater Harvesting Systems
SR	Spatial Resolution
SWIR	Shortwave Infrared
TASI	Thermal Airborne Spectrographic Imager
TES	Temperature Emissivity Separation
TIR	Thermal Infrared
UA	Urban Agriculture
UAB	Universitat Autònoma de Barcelona
UAc	User's Accuracy
UAGR	Urban Agri-Green Roofs
UHI	Urban Heat Island
UPC	Universitat Politècnica de Catalunya
VIS	Visible

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Summary

Urban agriculture (UA), rainwater harvesting, and solar energy systems are increasingly present in cities, especially in developed countries as responses to achieve urban sustainability. Contributing to the management of resources, mitigate climate change, and in the case of the UA, also in educational and social aspects. These local resource generation approaches present various benefits, for example, they satisfy the demand for food in cities, develop social inclusion, reduce environmental impacts such as transport emissions, and generate positive social, educational, and environmental impacts, as well as they can contribute to the development of local economies, strongly linked to the development of a circular economy. The above aspects contribute positively to the urban ecosystem. However, different problems related to land in cities, especially but not only in compact cities, such as the lack and high cost of land, represent a challenge to produce local resources. The roofs of the buildings represent a large percentage of the surface of the cities, which are generally empty spaces use, for these reasons, the roofs are an alternative to integrate rooftop urban agriculture (RUA), rainwater harvesting systems (RHS) and photovoltaic (PV) systems. However, the studies and tools to assess the integration potential of AUC, CAL, and PV from a holistic perspective, as well as the barriers, opportunities, and factors that arise concerning the recent focus of urban agriculture in buildings are limited, in this sense, research is needed that focuses on these aspects. This thesis aims to study these gaps by addressing the following research questions:

1. What are the steps to acquire spectral data from roof materials at laboratory-scale and what are the spectral characteristics of these materials?

2. Are hyperspectral remote sensing a reliable tool to identify roof materials in cities?

3. What approach is most suitable to identify and quantify the feasibility of rooftops to integrate urban agriculture (rooftops greenhouses (RTGs) and open-air), rainwater harvesting, and solar energy systems in residential and non-residential urban areas?

4. Which are the key factors, legal constraints, barriers, opportunities, and their perceived effect on RUA diffusion and in which scale and project's life cycle stage are presented?

This thesis implicates different dimensions: technological, environmental, and social; various scales: laboratory, building, urban; different urban forms: compact and diffuse; and distinct disciplines: agricultural, architectural, urban planning, and environmental. The thesis is mainly based on remote sensing technology and social tools described in the following paragraphs.

To address the first research question, a novel framework was developed for acquire spectral data of roofs at laboratory scale. The reflectance data of roof materials were obtained using a high-spatial-resolution (HSR) sensor, the System for Different Applications (AISA) Eagle II. The main results demonstrated large variations in the spectral reflectance due to the composition of the roof material. Flat spectral signatures were found for fiber cement, concrete, gravels, and some metals, especially from the near-infrared (NIR) spectral region. Colour and surface finish influence the visible (VIS) spectral range. The view angle did not modify the spectral shapes. In addition, a collection of 39 spectral data were compiled into a spectral library that is available online. In future work it is recommended to consider methodological aspects, for example, considerations of the aging process of the materials or the inclusion of data with short wave infrared (SWIR) spectral range and more extensive analysis regarding spectral separability.

The second research question was addressed by mapping roofing materials on a city scale. To identify the classes of materials, first, a flight operated with the two hyperspectral remote sensors was performed simultaneously, additionally light and range detection (LiDAR) data was used. The study area was the Vallès Occidental, a Mediterranean county north of Barcelona (Spain), the total area was 15 km^2. Different types of buildings, building uses (residential, industrial, offices, services, and commerce), urban forms and population densities constitute the study area. Seven different classes of roofs were identified from the hyperspectral images acquired by the airborne sensors and the application of the k-means algorithm. To validate the classification results, 237 roof polygons were verified using three different methods: visual inspection, information from field experts, and field inspection. The results demonstrated that hyperspectral imaging data is a powerful tool for mapping roof materials in urban environments. The overall accuracy and the Kappa coefficient was 75% and 0.7, respectively. Some problems in the classification process, such as those related to treetops and infrastructure elements on roofs, need to be addressed in future studies as they decrease the precision.

To answer the third question, first a framework was developed to identify and analyse roof feasibility for integrating UA, RWHS, and PV systems using various remote sensing. The development of the methodology focused mainly on establishing urban, climatic, and architectural criteria, including minimum natural light requirements for three groups of crops: (1) tomatoes, (2) strawberries and leaf crops, and (3) microgreens. In addition, criteria were defined for commercial and self-consumption purposes. Data acquisition was based on the use of remote sensing and GIS systems. Finally, quantification of production potential and self-sufficiency of resources (food, water and energy) was described. The framework was applied to the Vallès Occidental a Mediterranean county. The case study included compact and disperse urban forms, residential and non-residential building uses, and various building typologies. Main results showed that 8% of the roof area is feasible for tomato and lettuce production, these crops could satisfy the average intake of tomatoes of 210% and the average intake of lettuce of 21% of the population. RWHS could supply 63% of the water requirements for tomato growing in an open-air system and 53% of irrigation for tomato production in RTGS. The results showed a potential of 82% of roofs for RWHS, representing the average yearly water consumption of 44% of citizens for laundry, showering, toilet flushing, cleaning and irrigation uses. Finally, 50% of the roofs are suitable for PV, representing an average energy consumption of 18%of citizens.

To address the fourth question two studies were conducted. The first study consisted of two phases. The first phase a workshop was developed the second phase consisted of a survey applied to RUA stakeholders from four European cities (Barcelona, Berlin, Bologna, and Paris). Subsequently, a study focused on the city of Barcelona was carried out. A participatory process (World Café) with those involved in the First Green Roofs Competition in Barcelona was developed. The results of this work highlighted that environmental factors, technological innovation, research, education, food production, the revaluation of productive spaces, cultural values, the rural-urban social link, social cohesion, and the high cost of land play an important role in the implementation of RUA. The cost of water and pollution stand out as the main limiting contextual factors. Policies related to financial incentives, development of new technologies, education, food production, the Milan pact, and the Parisculteurs program promote RUA. The main architectural and technical barriers were building height limits, restrictions for integration into historic buildings and a gap in the urban code, the need for structural reinforcement of the building, the precondition of the building envelope, and its load-bearing capacity. The main economic barriers were high infrastructure costs, initial investment, and policies prohibiting the commercialization of products. Lack of information and social cohesion. Urban barriers included the lack of consideration of agricultural land use. The main opportunities were social cohesion; improvement of the quality of life; new specific regulations; profits derived from RUA projects; and aesthetic improvement. The results showed that most of the barriers and opportunities are at the building and city levels.

In terms of life cycle stage, most opportunities appear during the use stage (84%), while barriers appear mainly during the project stage (62%). According to the results, there is a need for the dissemination and development of appropriate information on RUA, as well as the creation of new regulations and modifications to urban and building codes to support RUA to allow agriculture to take place in cities and regulations regarding marketing for RUA-derived products.

This thesis contributes mainly to the knowledge of RUA in addition to RWHS, and PV systems, the use of remote sensing technology in cities as well as stakeholders' perceptions by developing frameworks and generating data on the topics studied. The results obtained close the gaps between technical requirements using RS for integrating RUA, RWHS, and PV in cities and the barriers and opportunities, which must be addressed to promote RUA. This thesis provides support to the decision-making processes for different stakeholders but especially to urban planners and architects and provides a methodological basis for its application in other cities around the world.

Future research should focus on acquiring spectral data of roofing materials from different geographical areas, evaluating urban ecological indicators based on automated material mapping, identifying critical points in cities to prioritize urban greening, characterization, and analysis of different urban structures. In addition, the development of interactive and accessible information on potential rooftops is needed. Additionally, new digital tools such as specialized software in this field are required to evaluate potential rooftops. Design of new buildings considering systems and integration of food, water, and energy flows, as well as social, economic, and environmental dimensions. Finally, the development of barrier and opportunity studies considering the new findings reported in this thesis and possible associated risks such as gentrification is recommended. The environmental assessment of rooftop greenhouses, the identification of differences and similarities in different cities, the evaluation, and comparison of perceptions regarding existing infrastructures, the development of social and educational programs, and the inclusion of pilot projects in other cities.

Resum

L'agricultura urbana (UA per les seves sigles en anglès), la captació d'aigua de pluja i els sistemes d'energia solar, estan cada vegada més presents a les ciutats, especialment en els països desenvolupats com respostes per aconseguir la sostenibilitat urbana. Aquests enfocaments de generació de recursos locals presenten diversos beneficis, per exemple satisfan la demanda d'aliments a les ciutats, generen inclusió social, redueixen els impactes ambientals com les emissions del transport i generen impactes positius en el social, educatiu, ambiental més poden contribuir al desenvolupament de les economies locals, fortament vinculades al desenvolupament d'una economia circular, els aspectes anteriors, contribueixen positivament a l'ecosistema urbà. No obstant això, diferents problemàtiques relacionades amb el sòl a les ciutats, especialment, però no únicament en les ciutats compactes, com la falta i l'alt cost de la terra, representen un desafiament per a la producció de recursos locals. Les cobertes dels edificis representen un gran percentatge de la superfície de les ciutats, que generalment són espais buits sense ús, per aquests motius, els terrats són una alternativa per integrar l'agricultura urbana en coberta (RUA per les seves sigles en anglès), els sistemas de captació d'aigua de pluja (RWHS per les seves sigles en anglès) i els sistemes fotovoltaics (PV per les seves sigles en anglès). No obstant això, els estudis i eines per avaluar la potencial integració de RUA, RWHS i PV des d'una perspectiva holística, així com les barreres, oportunitats i factors pel que fa al recent enfocament de l'agricultura urbana en els edificis són limitats, en aquest sentit, calen investigacions que s'enfoquin en aquests aspectes. Aquesta tesi té com a objectiu omplir aquests buits abordant les següents preguntes d'investigació:

1. Quins són els passos per adquirir dades espectrals de materials de sostre a escala laboratori i quines són les característiques espectrals d'aquests materials?

2. És la teledetecció hiperespectral una eina fiable per identificar els materials dels sostres a les ciutats?

3. Què enfocament és el més adequat per a identificar i quantificar la viabilitat de les cobertes dels edificis per integrar l'agricultura urbana (hivernacles i a l'aire lliure), la captació d'aigua de pluja i els sistemes d'energia solar en àrees urbanes residencials i no residencials?

4. Quins són els factors clau, restriccions legals, barreres i oportunitats i el seu efecte percebut en la difusió de la RUA, i a quina escala i etapa del cicle de vida d'el projecte es presenten?

Aquesta tesi implica diferents escales: laboratori, edificació, urbana i social; formes urbanes: compacta i difusa; diferents dimensions: tecnològica, ambiental i social; i disciplines: agrícoles, arquitectòniques, urbanístiques i mediambientals. La tesi es basa principalment en tecnologia de teledetecció i eines socials.

Per abordar la primera pregunta, es va desenvolupar un marc de referència nou per a l'adquisició de dades espectrals basats en laboratori, l'anterior, per caracteritzar els materials de les cobertes de les ciutats. L'adquisició de dades es va dur a terme en un laboratori utilitzant un sensor d'alta resolució espacial, específicament es va usar el sistema per a diferents aplicacions (AISA per les sigles en anglès) Eagle II, un generador d'imatges hiperespectrals que cobreix el rang espectral visible i infraroig proper (VNIR per les sigles en anglès). Amb el marc de referència desenvolupat, es van obtenir les dades de reflectància de diversos materials de les cobertes. Els principals resultats van demostrar grans variacions en les dades de reflectància espectral a causa de la composició del material. Es van trobar signatures espectrals planes per fibrociment, formigó, graves i alguns metalls, especialment a la regió

espectral de l'infraroig proper (NIR per les sigles en anglès). Es va identificar que tant el color com l'acabat de la superfície influeixen en el rang espectral visible (VIS). L'angle de visió no va modificar les formes espectrals. Per contribuir al coneixement de les característiques espectrals dels materials de les cobertes, es va compilar una col·lecció de 39 dades espectrals en una biblioteca espectral que està disponible en línia.

La segona pregunta de recerca es va abordar mitjançant el mapeig dels materials de les cobertes a escala ciutat. Es va realitzar un vol operat amb els dos sensors remots hiperspectrals simultàniament, addicionalment es van utilitzar dades de detecció de llum i abast (LiDAR per les sigles en anglès). L'àrea d'estudi va ser al Vallès Occidental, un comtat mediterrània a nord de Barcelona (Espanya), l'àrea total va ser de 15 km^2. Diferents tipologies, usos d'edificis (residencial, industrial, oficines, serveis i comerç), formes urbanes i densitats de població constitueixen l'àrea d'estudi. Es van identificar set classes de cobertes, a partir de les imatges hiperespectrals adquirides pels sensors aeris i l'aplicació de l'algoritme d'agrupació de k-mitjanes. Per validar els resultats, es va realitzar una verificació de 237 polígons de cobertes, utilitzant tres mètodes diferents: inspecció visual, informació d'experts de camp i inspecció en camp. Els resultats van demostrar que les dades de les imatges hiperespectrals són una eina potent per mapejar els materials de les cobertes en entorns urbans. La precisió general i el coeficient Kappa va ser de 75% i 0,7, respectivament. Alguns problemes en el procés de classificació, com els relacionats amb les copes d'arbres i elements d'infraestructura sobre les cobertes, s'han d'abordar en futurs estudis ja que disminueixen la precisió. Així com explorar el suso d'altres algoritmes i incorporar dades de heperspectrales SWIR.

Per respondre la tercera pregunta, es va desenvolupar un marc de referència per a identificar i analitzar la viabilitat de les cobertes per a la integració de la AU, la recol·lecció d'aigua de pluja i els sistemes fotovoltaics. El desenvolupament de la metodologia es va enfocar principalment en establir criteris urbans, climàtics i arquitectònics, incloent els requeriments mínims de llum natural per tres grups de cultius: (1) tomàquets, (2) maduixes i cultius de fulles i (3) microgreens. A més, es van definir criteris per a fins comercials i d'autoconsum. L'adquisició de dades es va basar en l'ús de sistemes de teledetecció i GIS. Finalment, es va descriure la quantificació de l'potencial de producció i autosuficiència dels recursos (aliments, aigua i energia). La proposta metodològica es va aplicar a un comtat de l'Vallès Occidental (Barcelona). Per a la caracterització de les cobertes i edificis es van utilitzar tres sensors remots d'alta resolució espacial AISA Eagle II, TASI 600 i LiDAR. L'àrea d'estudi va incloure formes urbanes compactes i disperses, usos d'edificis residencials i no residencials i diverses tipologies d'edificis. Els resultats van mostrar que el 8% de les cobertes són factibles per a la producció de tomàquet i enciam, aquests cultius podrien satisfer el consum mitjà anual de lo 210% del tomàquets i el 21% d'enciam. Pel que fa als sistemes de recollida d'aigua de pluja, podrien suplir el 63% de les necessitats hídriques de cultius de tomàquet en un sistema a l'aire lliure i el 53% de l'reg per a la producció en sistemes d'hivernacle. El 82% l'àrea de les cobertes dels edificis es podria utilitzar per a la integració de sistemes de recollida d'aigua de pluja, el que representa el consum mitjà anual d'aigua de el 44% de la població. Finalment, el 50% de les cobertes són aptes per a PV, el que suposa el consum energètic mitjà anual de l'18% dels habitants. És recomanable la inclusió d'indicadors d'impacte ambiental, socials i econòmics. La integració de criteris tècnics i arquitectònics considerant noves tecnologies com fotovoltaiques transparents, i altres sistemes de gestió de recursos hídrics.

Per abordar la quarta pregunta es van realitzar dos estudis. El primer estudi va constar de dues fases. La primera fase es va desenvolupar un taller. La segona fase va consistir en una enquesta aplicada a les parts interessades en RUA de quatre ciutats europees (Barcelona, Berlín, Bolonya i París). Posteriorment, es va dur a terme un estudi centrat en la ciutat de Barcelona. Es va desenvolupar un procés participatiu (World Café) amb els participants al Primer Concurs de Teulades Verdes a Barcelona. Els resultats d'aquest treball van destacar que els factors ambientals, d'innovació tecnològica, investigació, educació, producció d'aliments, la revalorització dels espais productius, els valors culturals, el vincle social rural-urbà, la cohesió social i l'alt cost de la terra juguen un paper important en la implementació de la RUA. El cost de l'aigua i la contaminació destaquen com els principals factors contextuals limitants. Les polítiques relacionades amb els incentius financers, el desenvolupament de noves tecnologies, l'educació, producció alimentària, el pacte de Milà i el programa Parisculteurs promouen la RUA. Les principals barreres arquitectòniques i tècniques van ser els límits de l'altura de l'edifici, les restriccions per a la integració en edificis històrics i un buit de el codi urbà, la necessitat de reforç estructural de l'edifici, la condició prèvia de la coberta de l'edifici i la seva capacitat de càrrega. Les principals barreres econòmiques van ser alts costos de la infraestructura, la inversió inicial i les polítiques que prohibeixen la comercialització de productes. La manca d'informació i de cohesió social. En les barreres urbanes es va destacar la nul·la consideració d'ús de sòl agrícola. Les principals oportunitats van ser la cohesió social; millora de la qualitat de vida; nova normativa específica; les utilitats derivades dels projectes de RUA; i millora estètica. Els resultats van mostrar que la majoria de les barreres i oportunitats es presenten a nivell edifici i ciutat. Pel que fa a l'etapa de l'cicle de vida, la majoria de les oportunitats apareixen durant l'etapa d'ús (84%), mentre que les barreres apareixen principalment durant l'etapa de projecte (62%). D'acord amb els resultats és necessària la difusió i el desenvolupament d'informació apropiada sobre RUA, així com la creació de noves regulacions i modificacions als codis urbans i de construcció per donar suport a la RUA que permeti que l'agricultura es dugui a terme a les ciutats i regulacions referents a l'màrqueting per als productes derivats de RUA.

Aquesta tesi contribueix amb metodologies i generació de noves dades principalment en el camp de l'agricultura urbana a les cobertes dels edificis. Els resultats obtinguts tanquen les bretxes entre els requeriments tècnics i la tecnologia de teledetecció per a la integració de RUA, RWHS i PV a les ciutats. També es fa una aportació a l'estat de l'art sobre les barreres i oportunitats que s'han d'abordar per promoure la RUA destacat llacunes no reportades en investigacions prèvies. Aquesta tesi dóna suport als processos de presa de decisions de diferents actors, especialment a urbanistes i arquitectes i bases metodològiques per a la seva aplicació en altres ciutats de l'món.

Les investigacions posteriors haurien de centrar-se en l'adquisició dades espectrals de materials de cobertes de diferents àrees geogràfiques, avaluar indicadors ecològics urbans basats en el mapatge automatitzat de materials, identifiquen dels punts crítics en les ciutats per prioritzar el verd urbà, caracterització i anàlisi de diferents estructures urbanes. A més, és necessari el desenvolupament d'informació interactiva i accessible sobre els terrats potencials. Es necessiten noves eines digitals com a programari especialitzat en aquest camp per avaluar les cobertes potencials. Disseny de nous edificis considerant els sistemes i la integració dels fluxos d'aliments, aigua i energia, així com les dimensions socials, econòmiques i ambientals. Finalment, es recomana el desenvolupament d'estudis de barreres i oportunitats considerant les noves troballes reportats i possibles riscos associats com la gentrificació. L'avaluació ambiental d'hivernacles en coberta, la identificació de diferències i semblances en diferents ciutats, l'avaluació i comparació de percepcions respecte a infraestructures existents, el desenvolupament de programes socials i educatius i la inclusió de projectes pilot en altres ciutats.

Resumen

La agricultura urbana (AU), la recolección de agua de lluvia y los sistemas de energía solar, están cada vez más presentes en las ciudades, especialmente en los países desarrollados como respuestas para lograr la sostenibilidad urbana. Estos enfoques de generación de recursos locales presentan diversos beneficios, por ejemplo, satisfacen la demanda de alimentos en las ciudades, se desarrolla la inclusión social, reducen los impactos ambientales, como las emisiones del transporte y generan impactos positivos en lo social, educativo y ambiental, además pueden contribuir al desarrollo de las economías locales, fuertemente vinculadas al desarrollo de una economía circular. Los aspectos anteriores, contribuyen positivamente al ecosistema urbano. Sin embargo, diferentes problemáticas relacionadas con la falta de suelo y el alto costo de la tierra en las ciudades representan un desafío para la producción de recursos locales, especialmente (pero no únicamente) en las ciudades compactas. Las cubiertas de los edificios son espacios generalmente sin uso en los que se puede integrar la agricultura urbana en cubierta (RUA por sus siglas en inglés), sistemas de captación de agua de lluvia (RWHS por sus siglas en inglés) y los sistemas fotovoltaicos (PV por sus siglas en inglés). Sin embargo, los estudios y herramientas para evaluar el potencial de integración de RUA, RWHS y PV desde una perspectiva holística, así como las barreras, oportunidades y los factores claves que se presentan al reciente enfoque de la RUA son limitados. En este sentido, es necesario desarrollar investigaciones orientadas en estos tópicos, para lo cual la presente tesis abordó las siguientes preguntas de investigación:

1. ¿Cuáles son los pasos para adquirir datos espectrales de materiales de techo a escala laboratorio y cuáles son las características espectrales de estos materiales?
2. ¿Es la teledetección hiperespectral una herramienta confiable para identificar los materiales de los techos en las ciudades?
3. ¿Qué enfoque es el más adecuado para identificar y cuantificar la viabilidad de las cubiertas de los edificios para integrar la agricultura urbana (invernaderos y al aire libre), la captación de agua de lluvia y los sistemas de energía solar en áreas urbanas residenciales y no residenciales?
4. ¿Cuáles son los factores clave, restricciones legales, barreras y oportunidades y su efecto percibido en la difusión de la RUA, y a qué escala y etapa del ciclo de vida del proyecto se presentan?

Para dar respuesta a las preguntas planteadas, esta tesis engloba diferentes escalas laboratorio, edificio, urbana y social; dimensiones tecnológica, ambiental y social; así como distintas formas urbanas compacta y difusa; además comprende diversas disciplinas agrícolas, arquitectónicas y urbanísticas. La tesis se basa principalmente en el uso de tecnología de teledetección y herramientas sociales.

Para abordar la primera pregunta de investigación, se desarrolló un marco de referencia para la adquisición de datos espectrales en laboratorio. Para la adquisición de datos se utilizó un sensor de alta resolución espacial System for Different Applications (AISA por sus siglas en inglés) Eagle II. Los principales resultados demostraron grandes variaciones en los datos espectrales debido a la composición del material. Se encontraron firmas espectrales planas para fibrocemento, hormigón, gravas y algunos metales, especialmente en la región espectral del infrarrojo cercano (NIR por sus siglas en inglés). Se identificó que tanto el color como el acabado de la superficie influyen en el rango espectral visible (VIS). También se encontró que el ángulo de visión no modifica las huellas espectrales. Además, se compiló una colección de 39 materiales con datos gráficos y numéricos (biblioteca espectral) disponible en línea. En

futuros trabajos se recomienda considerar aspectos metodológicos, por ejemplo, consideraciones del proceso de envejecimiento de los materiales o la inclusión de datos con rango espectral infrarrojo de onda corta (SWIR por sus siglas en inglés) y análisis más extensos respecto a la separabilidad espectral.

La segunda pregunta de investigación se abordó mediante el mapeo de los materiales de cubiertas a escala ciudad. Se realizó un vuelo operado con los dos sensores remotos hiperspectrales simultáneamente, adicionalmente se utilizaron datos de detección de luz y alcance (LiDAR por sus siglas en inglés). El área de estudio fue el Vallès Occidental, en un condado mediterránea al norte de Barcelona (España), el área total fue de 15 km^2. Diferentes tipologías, usos de edificios (residencial, industrial, oficinas, servicios y comercio), formas urbanas y densidades de población constituyen el área de estudio. Se identificaron siete clases de cubiertas, a partir de las imágenes hiperespectrales adquiridas por los sensores aéreos y la aplicación del algoritmo de agrupación de k-medias. Para validar los resultados, se realizó una verificación de 237 polígonos de cubiertas, utilizando tres métodos diferentes: inspección visual, información de expertos de campo e inspección en campo. Los resultados demostraron que los datos de las imágenes hiperespectrales son una herramienta potente para mapear los materiales de las cubiertas en entornos urbanos. La precisión general y el coeficiente Kappa fue de 75% y 0,7, respectivamente. Algunos problemas en el proceso de clasificación, como los relacionados con las copas de árboles y elementos de infraestructura sobre las cubiertas, deben abordarse en futuros estudios ya que disminuyen la precisión. Así como explorar el suso de otros algoritmos e incorporar datos de hiperspectrales SWIR.

Para responder la tercera pregunta, se desarrolló un marco de referencia para identificar y analizar la viabilidad de las cubiertas para la integración de la AU, la recolección de agua de lluvia y los sistemas fotovoltaicos. El desarrollo de la metodología se enfocó principalmente en establecer criterios urbanos, climáticos y arquitectónicos, incluyendo los requerimientos mínimos de luz natural para tres grupos de cultivos: (1) tomates, (2) fresas y cultivos de hojas y (3) microgreens. Además, se definieron criterios para fines comerciales y de autoconsumo. La adquisición de datos se basó en el uso de sistemas de teledetección y GIS. Por último, se describió la cuantificación del potencial de producción y autosuficiencia de los recursos (alimentos, agua y energía). La propuesta metodológica se aplicó a un condado del Vallès Occidental (Barcelona). Para la caracterización de las cubiertas y edificios se utilizaron tres sensores remotos de alta resolución espacial AISA Eagle II, TASI 600 y LiDAR. El área de estudio incluyó formas urbanas compactas y dispersas, usos de edificios residenciales y no residenciales y diversas tipologías de edificios. Los resultados mostraron que el 8% de las cubiertas son factibles para la producción de tomate y lechuga, estos cultivos podrían satisfacer el consumo promedio anual del 210% de tomates y 21% de lechuga. Respecto a los sistemas de recolección de agua de lluvia, podrían suplir el 63% de las necesidades hídricas de cultivos de tomate en un sistema al aire libre y el 53% del riego para la producción en sistemas de invernadero. El 82% del área de las cubiertas de los edificios se podría utilizar para la integración de sistemas de recolección de agua de lluvia, lo que representa el consumo promedio anual de agua del 44% de la población. Finalmente, el 50% de las cubiertas son aptas para PV, lo que supone el consumo energético medio anual del 18% de los habitantes. Es recomendable la inclusión de indicadores de impacto ambiental, sociales y económicos. La integración de criterios técnicos y arquitectónicos considerando nuevas tecnologías como fotovoltaicas transparentes, y otros sistemas de gestión de recursos hídricos.

Para abordar la cuarta pregunta se utilizaron dos estudios. El primero englobó dos fases; la primera fase constó de un taller, la segunda fase consistió en el desarrollo y aplicación de una encuesta a las partes involucradas en materia de RUA de cuatro ciudades europeas (Barcelona, Berlín, Bolonia y París). El segundo estudio se centró en la ciudad de Barcelona. Se desarrolló un proceso participativo (World Café) con involucrados en el Primer Concurso de Cubiertas Verdes de Barcelona. Los resultados de este trabajo destacaron que los factores ambientales, de innovación tecnológica, investigación, educación, producción de alimentos, la revalorización de los espacios productivos, los valores culturales, el vínculo social rural-urbano, la cohesión social y el alto costo de la tierra juegan un papel importante en la implementación de la RUA. El costo del agua y la contaminación destacan como los principales factores contextuales limitantes. Las políticas relacionadas con los incentivos financieros, el desarrollo de nuevas tecnologías, la educación, producción alimentaria, el pacto de Milán y el programa Parisculteurs promueven la RUA. Las principales barreras arquitectónicas y técnicas fueron los límites de la altura del edificio, las restricciones para la integración en edificios históricos y un vacío del código urbano, la necesidad de refuerzo estructural del edificio, la condición previa de la cubierta del edificio y su capacidad de carga. Las principales barreras económicas fueron altos costos de la infraestructura, la inversión inicial y las políticas que prohíben la comercialización de productos. La falta de información y de cohesión social. En las barreras urbanas se destacó la nula consideración de uso de suelo agrícola. Las principales oportunidades fueron la cohesión social; mejora de la calidad de vida; nueva normativa específica; las utilidades derivadas de los proyectos de RUA; y mejora estética. Los resultados mostraron que la mayoría de las barreras y oportunidades se presentan a nivel edificio y ciudad. En cuanto a la etapa del ciclo de vida, la mayoría de las oportunidades aparecen durante la etapa de uso (84%), mientras que las barreras aparecen principalmente durante la etapa de proyecto (62%). De acuerdo con los resultados es necesaria la difusión y el desarrollo de información apropiada sobre RUA, así como la creación de nuevas regulaciones y modificaciones a los códigos urbanos y de construcción para respaldar la RUA que permita que la agricultura se lleve a cabo en las ciudades y regulaciones referentes al marketing para los productos derivados de RUA.

Esta tesis contribuye con metodologías y generación de nuevos datos principalmente en el campo de la agricultura urbana en las cubiertas de los edificios. También se hace un aporte al estado del arte sobre las barreras y oportunidades que deben abordarse para promover la RUA destacado lagunas no reportadas en investigaciones previas. Esta tesis da soporte a los procesos de toma de decisiones de diferentes actores, especialmente a urbanistas y arquitectos y bases metodológicas para su aplicación en otras ciudades del mundo.

Futuras investigaciones deben centrarse en adquirir datos espectrales de materiales de cubiertas de diferentes áreas geográficas, evaluar indicadores ecológicos urbanos basados en el mapeo automatizado de materiales, identifican de los puntos críticos en las ciudades para priorizar el verde urbano, caracterización y análisis de diferentes estructuras urbanas. Además, es necesario el desarrollo de información interactiva y accesible sobre las azoteas potenciales. Adicionalmente, se necesitan nuevas herramientas digitales como software especializado en este campo para evaluar las cubiertas potenciales. Diseño de nuevos edificios considerando los sistemas y la integración de los flujos de alimentos, agua y energía, así como las dimensiones sociales, económicas y ambientales. Finalmente, se recomienda el desarrollo de estudios de barreras y oportunidades considerando los nuevos hallazgos reportados en la presente tesis y posibles riesgos asociados como la gentrificación. La evaluación ambiental de invernaderos en cubierta, la identificación de diferencias y similitudes en distintas ciudades, la evaluación y comparación de percepciones respecto a infraestructuras existentes, el desarrollo de programas sociales y educativos y la inclusión de proyectos piloto en otras ciudades.

Preface

This doctoral thesis was developed from February 2017 to July 2021 within the Ph.D program of *Environmental Science and Technology* offered by the Institute of Environmental Science and Technology (ICTA-UAB) of the Universitat Autònoma de Barcelona (UAB). It was developed in collaboration with the research group of Sustainability and Environmental Prevention (Sostenipra; 3.0 2017SGR 1683) at the ICTA-UAB facilities; this institute was awarded with María de Maeztu program for Units of Excellence in R&D (MDM-2015-0552). The research was conducted within the framework of the Fertilecity II project (MINECO/FEDER, UE: CTM2016-75772-C3-1-R; CTM2016-75772-C3-3-R) "*Integrated rooftop greenhouses: energy, waste and CO_2 symbiosis with the building. Towards foods security in a circular economy*". This project was coordinated by the Institute of Environmental Science and Technology (ICTA-UAB), Universitat Autònoma de Barcelona and developed in collaboration with the Universitat Politècnica de Catalunya (UPC) and was supported by the pre-doctoral fellowship awarded by the Universidad de Guadalajara (Mexico) from February 2017 to January 2020.

The dissertation considers a multidisciplinary approach in the fields of architecture, urban planning, remote sensing, geographic information systems (GIS) and environmental, social, and agronomic sciences to propose and evaluate tools and frameworks for assessing the potential integration of food production, rainwater harvesting, and solar energy systems on rooftops at city and building scale in a Mediterranean region located in the metropolitan area of Barcelona. Works related to remote sensors were carried out with the collaboration with the Institut Cartogràfic i Geològic de Catalunya, (ICGC) due a contract between UPC and ICGC. The thesis provides knowledge in terms of remote sensing technology applications and identifies the implications of various fields in the integration of agro-green roofs in Barcelona. The dissertation provides frameworks that are replicable to other geographic areas to characterize roofs (geometrically and spectrally) using different high spatial resolution airborne sensors, to identify feasible areas to integrate food, water, and energy systems holistically; and to identified barriers and opportunities for integrating rooftop urban agriculture in cities.

Chapter three of this dissertation is based on the following published article in a peer-reviewed indexed journal from the first quartile:

- **Zambrano-Prado, P.**, Josa, A., Rieradevall, J., Pérez-Aragüés, F., Marchan, J. F., Gassó-Domingo, S., & Gabarrell, X. (2020). Laboratory-based spectral data acquisition of roof materials. International Journal of Remote Sensing, 41(23), 9180-9205. https://doi.org/10.1080/01431161.2020.1798548

Chapter five of this dissertation is based on the following accepted article in a peer-reviewed indexed journal from the first quartile (pre-proof status when this thesis was finished):

- **Zambrano-Prado, P.**, Munoz-Liesa, J., Josa, A., Rieradevall, J., Alamús, R., Gasso-Domingo, S., & Gabarrell, X. (2021). Assessment of the food-water-energy nexus suitability of rooftops. Methodological remote sensing approach in an urban Mediterranean area. Sustainable Cities and Society, 103287. https://doi.org/10.1016/j.scs.2021.103287

Chapter six of this dissertation is based on the following accepted article in a peer-reviewed indexed journal (proof status when this thesis was finished):

- **Zambrano-Prado, P**; Orsini, F; Rieradevall, J; Josa, A & Gabarrell, X (2021) Potential Key Factors, Policies, and Barriers for Rooftop Agriculture in EU Cities: Barcelona, Berlin, Bologna, and Paris. Frontiers, Sustainable Food Systems, 5:733040. https://doi.org/10.3389/fsufs.2021.733040

Chapter seven of this dissertation is based on the following published article in a peer-reviewed indexed journal from the first quartile:

- **Zambrano-Prado, P.**, Pons-Gumí, D., Toboso-Chavero, S., Parada, F., Josa, A., Gabarrell, X., & Rieradevall, J. (2021). Perceptions on barriers and opportunities for integrating urban agri-green roofs: A European Mediterranean compact city case. Cities, 114, 103196. https://doi.org/10.1016/j.cities.2021.103196

In addition, the following oral communication and posters were presented in conferences as part of the doctoral thesis:

- **Perla Zambrano-Prado**, Xavier Gabarrell, Joan Rieradevall, Alejandro Josa. "*Urban materials characterization: spectral signatures for urban planning towards sustainable cities*". 1st International ICTA-UAB Spring Symposium. Barcelona, Spain, from 16th to 17th May 2018, Universitat Autonòma de Barcelona. (Oral communication).
- **Perla Zambrano-Prado**, Felipe Parada, Joan Muñoz, Verónica Arcas, Alejandro Josa, Joan Rieradevall, Xavier Gabarrell. "*Rooftop greenhouses for developing sustainable cities: identifying rooftop materials through hyperspectral remote sensing*". International Symposium on Advanced Technologies and Management for Innovative Greenhouses. Angers, France, from 16th to 20th June 2019. (Poster communication).
- **Perla Zambrano-Prado**, Susana Toboso-Chavero, Alejandro Josa, Santiago Gassó, Joan Rieradevall, Fernando Pérez, Juan Marchan, Ramón Alamús, Xavier Gabarrell. "*Urban typologies and building use for non-profit and commercial rooftop agriculture in cities: a Mediterranean case study*". 10th International Conference on Industrial Ecology. Beijing, China, from 7th to 11th July 2019. (Oral communication).
- Susana Toboso-Chavero, **Perla Zambrano-Prado**, Joan Rieradevall, Xavier Gabarrell. **"***Enhancing Cities' Performance: The Water-Energy-Food Nexus Implementation on Rooftops*". 10th International Conference on Industrial Ecology. Beijing, China, from 7th to 11th July 2019. (Oral communication).
- **Perla Zambrano-Prado**, Susana Toboso-Chavero, Alejandro Josa, Santiago Gassó, Joan Rieradevall, Fernando Pérez, Juan Marchan, Ramón Alamús, Xavier Gabarrell. "*Rainwater harvesting potential for rooftop greenhouses irrigation and CO_2 reduction in cities using airborne remote sensing*". The 9th International Conference on Life Cycle Management. Poznan, Poland from 1st to 4 th September 2019 (Poster communication).

Collaboration with the following workshop related to the goals of the dissertation was conducted during the thesis period:

- Metropolitan Agriculture for Developing an innovative, sustainable, and responsible economy. Organized by MedCities and Co-financed by the European Union. Barcelona, Spain, June 2017.
- Dani Zebelean. *Climate and rainwater harvesting supporting urban agriculture*. The International Research Experiences for Students funded by The National Science Foundation (U.S) program. Barcelona, Spain, June 2018 (Co Supervisor).
- Rochelle Plaizier. *Alternative Water Sources Support Urban Greenhouse Crops Feasibility of meeting urban greenhouse water needs with rainwater and greywater*. Experiences for Students funded by The National Science Foundation (U.S) program. Barcelona, Spain, June 2019 (Co Supervisor).

Participation as tribunal member of the following Master thesis related to the goals of the dissertation was done during the thesis period:

- Sally Bourdon. "*An Economic, Social, and Environmental Sustainability Analysis of implementing rooftop greenhouses in elderly residence facilities in Barcelona*". Barcelona, Spain. ICTA-UAB September 2018.
- Alba Lafarga Aguilar. "*Building up a Circular Economy on Critical Raw Materials: data for electronics*". Barcelona, Spain. ICTA-UAB September 2019.
- Simone Franco Merlo. "*Microalgae contribution to sustainable developed*". Barcelona, Spain. ICTA-UAB September 2019.

In addition, participation as co-supervisor of the following Master thesis related to the goals of the dissertation was carried out during the thesis period:

- Alejandro Rueda Gómez. "Feasibility of vertical farming in tropical weather: a case study in the city of Bogota". Barcelona, Spain. ICTA-UAB, September 2020.

The thesis is divided into five parts and ten chapters.

Part I Introduction, objectives, and general methods
It includes two chapters. **Chapter 1** presents a background of urban areas, food, water, and energy resources, remote sensing technology as a tool to acquire data of cities, and GIS also it defines the objectives of this thesis. **Chapter 2** describes the general framework and defines the methods, tools for data acquisition, scale of the study, and the main case study.

Part II Laboratory scale. Roofs spectral characterization
It has one chapter (**Chapter 3**). It describes a novel framework for laboratory-based spectral data acquisition to characterized roof materials of cities. Data acquisition was conducted in a laboratory under controlled conditions using a high-spatial-resolution (HSR) sensor, which is usually used for airborne surveys. Results of 39 spectral data were compiled into a spectral library that is available online.

Part III Building and Urban scale. Mapping and assessing roofs for food water and energy production in a Mediterranean region
It is composed of two chapters. **Chapter 4** describes the process for mapping roof materials at city scale using two hyperspectral remote sensors. A flight over the study, a Mediterranean region north of Barcelona (Spain) were performed with two sensors simultaneously. Seven roof classes were identified using spectral data and k-means clustering algorithm.

Chapter 5 describes a framework for assessing the feasibility of roofs in a Mediterranean area to integrate urban agriculture (rooftop greenhouses and open-air), rainwater harvesting, and photovoltaic systems on rooftops for commercial and non-profit purposes. Data acquisition is based on the use of remote sensing. Three airborne sensors were used for this purpose. Classification of roofs obtained from chapter 4 was used as a part of the evaluation of roofs.

Part IV Social scale. Potential barriers and opportunities for integrating urban agriculture on roofs
It includes two chapters. **Chapter 6** details an overview of potential key factors, policies, and barriers associated whit the integrations of RUA from stakeholder's perception in four European cities Barcelona, Berlin, Bologna and Paris. The study focuses on legal technical, environmental, educational, and economic fields. This chapter also explores the perceived effect on RUA diffusion and how much barriers are present for integrating RUA. Data acquisition was made in two phases, first a workshop was developed, then a survey was and applied to stakeholders from the European cities studied.

Chapter 7 analyses the perceived barriers and opportunities about the implementation of urban agro-green roofs. The study uses the world café method in the framework of The First Green Roofs Contest launched by Barcelona city, and explores real experiences from stakeholders involved in the stages of the project construction-use process.

Part V Discussion, conclusions, and further research
It is composed of two chapters. **Chapter 8** provides a general discussion of main contributions and **Chapter 9** describes general conclusions and **Chapter 10** describes recommendations for future research.

Dissertation structure

Figure 1 illustrates the structure of this thesis, organized in five main parts (1) introduction, objectives, and general methods, (2) Laboratory scale, (3) urban and building scale, (4) social scale, and (5) discussion, conclusions, and further research, a total of ten chapters were developed.

Figure 1. Structure of the thesis comprises five main parts and ten chapters

Part I

Introduction, objectives, and general methods

Chapter 1

Introduction and objectives

CHAPTER 1 - Introduction and objectives

This chapter introduces the general background of the phenomenon of urbanization focusing on their different effects on land, water, and energy and how food production, rainwater collection, and solar energy systems can be integrated on rooftops. A framework of remote sensing and its application in urban contexts is provided. Besides, a general introduction to geographic information systems is presented. Finally, this chapter defines and highlights the objectives of the dissertation.

1.1 Cities: urban development, growth, and urbanization

Urban development refers to the process of expansion of urban areas (Bajwa et al., 2015). There are two main processes involved in urban development. First, *urban growth* that refers to the increasing of population (demographic) and the increasing of area (spatial) in cities. This process occurs when population migrate from rural to urban areas and, therefore, demographic distribution changes from village to predominantly city-based (Bajwa et al., 2015; Viana et al., 2019). Second, *urbanization* that refers to the process of change from rural to urban life styles (Antrop, 2004). Nevertheless, *urbanization* is now used in a more general sense and refers to spatial growth of urban areas (Bajwa et al., 2015). The rapid growth of urban areas is influenced by two factors: population increase and migration to urban areas. Worldwide, more people are living in urban areas compared to rural ones. Figure 1.1 illustrates the evolution and projections of urban and rural world's population from 1950 to 2050. In 1950, 30% of global population was living in cities; currently, urban population is about 55% and by 2050 it is expected that around 68% of the world's population will reside in urban areas (United Nations, 2018a).

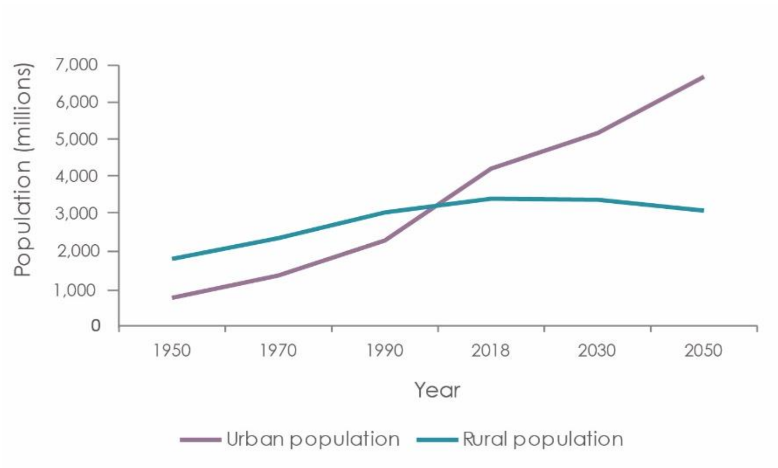

Figure 1.1. Evolution and projections of urban and rural world's population from 1950 to 2050. Own elaboration with data from United Nations (2018b).

Growing population will be responsible for a higher demand of resources. Figure 1.2 shows the projection in population, water, energy, and food demand increase that are expected, in all cases by over 50% in 2050 (International Renewable Energy Agency, 2015). Cities depend mainly on their surroundings to meet the demands of their citizens. This implies that cities impact extends over their boundaries (OECD, 2018). Increasing urban areas and therefore demand of resources have many environmental, economic, and social consequences (Rees & Wackernagel, 2008; Wilson & Chakraborty, 2013).

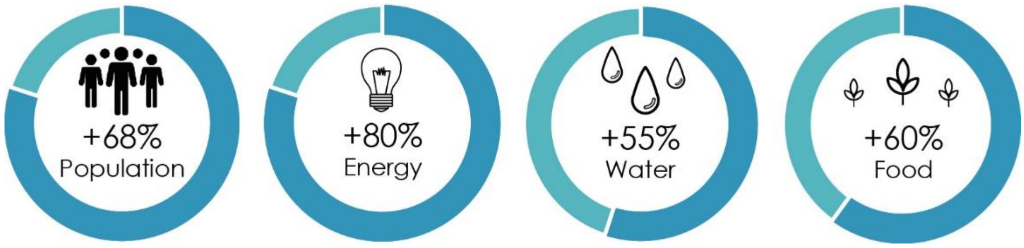

Figure 1.2. Estimated increase in population, water, energy, and food demand by 2050. Own elaboration with data from International Renewable Energy Agency (2015) and United Nations (2018b).

1.2 Urban growth and consequences

Cities cover 2% of the world's surface, and they are responsible for about 75% of the world's consumption of resources (Madlener & Sunak, 2011). Urban growth increases scarcity of resources and overexploitation. This section focuses on the consequences of urbanization, especially on land, water, and energy resources. Despite their quick growth, cities present a specific vulnerability with regard to the management of the food-water-energy (FWE) nexus and its elements, which illustrates the need for efforts to be made in terms of the use and optimization of natural resources (Toboso-Chavero et al., 2018). In this regard, cities have increased the pressure and exploitation levels imposed on the ecosystems, at both local and global scale (Ash et al., 2008), exerting a high impact on levels of atmospheric pollution and on the rising demand for natural resources. Currently, most cities have linear flows regarding inputs and outputs, characterized by import of resources and export of emissions (Wadel et al., 2010). Therefore, cities demonstrate the need for the development of more circular metabolisms which help to reduce the consumption of resources and energy and also increase opportunities for recycling, reuse and higher degrees of self-sufficiency with respect to the FWE nexus (Corcelli et al., 2019).

1.2.1 Loss of farmland

The demand of housing, commerce, industry, service, and transport infrastructure in cities, increase the pressure on land (European Environment Agency, 2015). To supply this demand, agricultural lands are converted into built-up areas (Berry, 1978). This process, creates competition, lack, and higher prices of land. Figure 1.3 shows the evolution and projections regarding urban land change in several regions. The loss of land for producing food has several consequences including a higher risk of food insecurity (FAO, 2011). Loss of fresh and local food products, higher demands on energy consumption and transport, degradation of ecological soil functions, landscape fragmentation, loss of habitat and species diversity are some of the consequences related to farmland loss that cities are facing (Bajwa et al., 2015; Rees & Wackernagel, 2008; Wilson & Chakraborty, 2013).

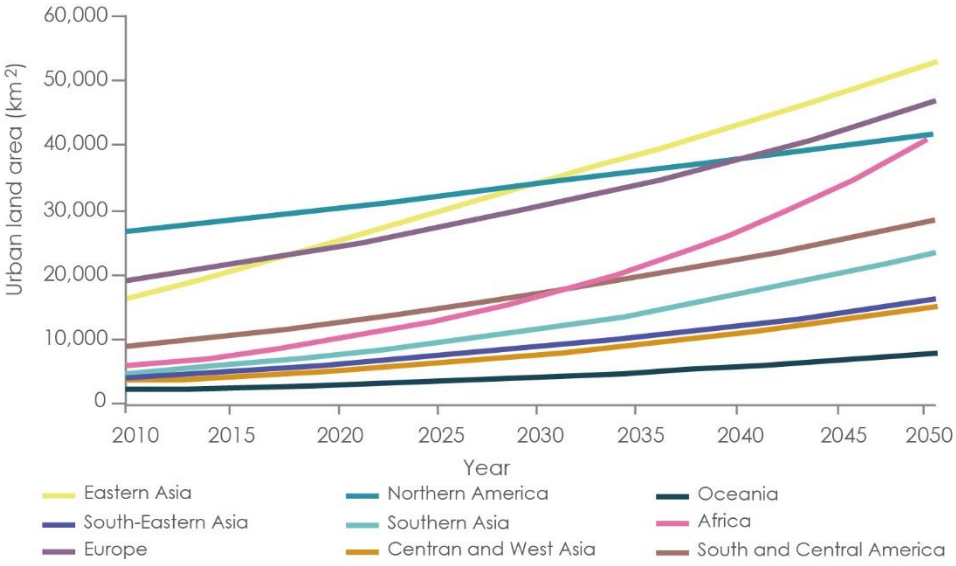

Figure 1.3. Urban land change in major global regions (United Nations Environment Programme, 2018).

1.2.2 Impacts on water

Urban areas are characterized by an increase of impervious surfaces (roads, parking lots, buildings). Imperviousness implies repercussions in water cycles, since rainwater remains on the surfaces and is unable to filter to the ground avoiding the recharge of groundwater aquifers. Many urban areas around the world are becoming increasingly water-stressed (Angrill et al., 2012a), and as a consequence, there is a water resources overexploitation, impacts in water balance, water supply and water competence, and increasingly exposition to water-related disasters with huge damages and economic losses due to floods in cities (Marcus, 2009).

1.2.3 Energy

Cities are responsible of two thirds of the total energy consumption and the 70% of the CO_2 emissions in the world (Madlener & Sunak, 2011). Urban growth brings new demands for long distances transport that increase the consumption of fossil fuels. Growing cities also means higher demand of energy in the construction sector, and maintenance of urban infrastructures (roads, bridges, sewage networks, power plants, and buildings). In addition, urban heat island implies higher demand of energy for air conditioning equipment.

1.3 Productive cities: increasing local resources

Local self-reliance (Morris, 1987) refers to the principle that population should be able to obtain their basic needs, like food, energy, water, and materials from within their own physical footprints (Grewal & Grewal, 2012). Given the spatial limitations in cities and the high competition in relation to space, roofs represent potent and large areas in cities to integrate FWE systems and to reduce environmental impacts, increase social cohesion and create circular economy in cities. This section describes strategies to produce resources in cities that can meet citizens demands of food, water, and energy as well as their potentials benefits.

1.3.1 Less space and more food: rooftop horticulture

Nowadays, 80% of the food stock in cities is supplied from rural areas and imports (Juniawati & Hayuningtyas, 2017). Thus, integration of strategies to provide enough food for a growing urban population becomes an urgent challenge (Farrell, 2017). In addition, the increased disconnection between consumers and food producers means that urban citizens have limited knowledge of issues associated with it. Food is transported over long distances, often by airplane, between regions and across continents. In some cases, local crops are replaced by commercial or non-seasonal crops. This structure of growing "food miles" is unsustainable because increases air pollution and contributes to greenhouse gas (GHG) emissions. (Viljoen et al., 2005). A study suggested that if food was produced organically and consumed locally the level of carbon dioxide emissions would be reduced by 22% in United Kingdom (Doron, 2005). UA represents an alternative to the current value chains with regard to meeting the demand for food in urban areas, and it can serve as an ideal tool to cover cities' food needs and, at the same time, develop a fundamental role in other areas of city life (Nadal, Cerón-Palma, et al., 2018; Sanyé-Mengual et al., 2016), related to economic, social, and environmental benefits (Benis et al., 2018a; Sanyé-Mengual et al., 2015b; Specht & Sanyé-Mengual, 2017). Empty spaces in cities such as rooftops are potent areas to produce food integrating, for example, open-air food production or rooftop greenhouses (RTGs) and reducing "food miles" (Benis et al., 2018b; Grewal & Grewal, 2012; Orsini et al., 2017). Thus, UA is an important aspect for urban sustainability (Viljoen et al., 2005).

1.3.2 Sustainable urban water

Rainwater harvesting played an important role in water supply in Mediterranean civilizations. Rainwater was collected in terracotta pipes to be stored in cisterns and then used in dry Mediterranean summers (Mays, 2014). Nowadays, the increasing demands on water supplies, particularly in urban areas, a significant decrease of freshwater supplies, and a lack of access to safe water make it necessary to find alternative solutions in water management (Ma et al., 2015). To satisfy water demand in cities, some solutions are based on the integration of rainwater harvesting systems (RWHS) that has the potential to reduce tap water consumption and provide water (Angrill et al., 2012a). These systems can serve as an independent water supply for different purposes including laundry, flushing, and irrigation. Large scale implementation of RWHS in cities, for instance in rooftops, could contribute to reduce environmental impacts, for example reducing energy (resulting in less greenhouse gas emissions) and avoiding stormwater peaks into the sewer system (Silva et al., 2015).

1.3.3 Solar energy

Several international organizations adopted renewable energy systems as a key to meet low-carbon development goals (Joss et al., 2013). By 2030, the overall European Union renewable energy sources consumption has to be 32% (The European Commission's science and knowledge service, 2019). However, PV parks located on land could greatly reduce the land for the agriculture sector, derived from land use competition between energy and food (Miskin et al., 2019). Some initiatives such as C40 Climate Leadership Group and the International Council on Local Environmental have challenged cities to integrate models based on decentralized energy supply (Byrne et al., 2015). In this sense, renewable technologies such as photovoltaic (PV) systems on roofs can significantly contribute to power capacity (Bódis et al., 2019). PV systems are a key element of energy-efficient buildings towards lower carbon-footprint buildings and decentralized energy systems in cities. Studies to determine rooftop PV potential have been performed on various regions and at different scales. Studies from USA, Canada, Spain, and Israel have found that PV on roofs could supply 15-45% of electricity consumption (Byrne et al., 2015).

1.4 Are cities embracing urban agriculture?

Even with the importance of UA in cities ecosystem, food production in urban contexts has remained excluded from urban planning until recently (Grewal & Grewal, 2012). Food planning has emerged as a legitimate part of planning agendas in developed and developing countries due to different reasons such as food security, climate change effects, land conflicts or rapid urbanization (Morgan, 2009).

In 1991, the city of Toronto created the Toronto Food Policy Council, one of North America's most efficient food policy councils. The city council played a key role in a wide range of municipal programs, including urban agriculture (Blay-Palmer, 2009). Municipal food policy in Vancouver is another example of a pioneer program for local food production. Local food policy started in 2003 when the city council approved the development of a just and sustainable food system' and a subsequent Food Action Plan was developed (Viljoen, 2014). New York City (NYC), Washington DC, Chicago, Toronto, Singapore and Paris initiated pioneer programmes related to food production on building rooftops. The New York City council developed the *FoodWorks A Vision to Improve NYC's Food System* plan, with the main objective of building a better food system and twelve specific objectives, divided into the following issues: agricultural production, processing, distribution, consumption, and post-consumption, agricultural production, aims to *increase urban food production*, and the proposals include the use of rooftops for growing food (The New York City Council, 2010). Other example is the city of Paris, through the *Parisculteurs* program the city of Paris supports rooftop urban agriculture projects, since the first call for projects in 2016, more than 48 projects have been developed (Ville de Paris, 2019). For example, Barcelona will host the international meeting of the Milan Pact, becoming the World Capital of Sustainable Food in 2021 (Barcelona City Council, 2020). Several programs regarding food system have emerged especially in North America. However, some regions and systems such as rooftop urban agriculture (RUA) remain excluded from urban planning policies.

New buildings can be designed and built considering RUA. Existent buildings can be rehabilitated for integrating RUA using different growing systems such as soil-less. The challenge faced by cities where RUA is emerging concerns to the creation or modification of instruments to promote RUA. In this regard, policies can act as a barrier to RUA integration (Freisinger et al., 2015). Four types of policy instruments to support UA have been identified: legal instruments (laws, by-laws, and ordinances); economic instruments (tax incentives or subsidies); educational instruments; and urban design instruments (Delshammar et al., 2017). In terms of policies aimed at promoting or regulating rooftop farming, Delshammar et al. (2017) indicated that there seem to be very few. In addition to legal instruments, other important topics such as social acceptance, technical, or architectural are related to barriers and opportunities for integrating RUA (Specht et al., 2016a) are present and few works have been developed. The literature indicates that there still a lack of information regarding policies, barriers, and opportunities around RUA.

1.5 Cities as a topic for remote sensing

As described in the last sections, the rapid expansion of urban areas constitutes an environmental challenge. City growth impacts can be mitigated by reducing the ecological footprint and making resources more efficient in cities. The goal of urban sustainability, according to Kadhim et al. (2016), is to manage resources and generate services through effective design. Urban sustainability requires access to urban data. This is a challenge where both new analytic approaches and new sources of data and information are needed (Kadhim et al., 2016; Miller & Small, 2003). According to Kumar (2005) remote sensing "is the science and art of obtaining information about an object, area, or phenomena, through the analysis of data, acquired by a device, that is not in contact with the object, area, or phenomena under investigation". Remotely sensed observations can facilitate the development of new tools and approaches to understand urban contexts. Advantages of data acquired from remote sensors (RS) include large spatial coverage and their capacity to provide consistent measurements of physical characteristics that would be expensive and laborious to obtain in situ.

The era of earth observation started in 1859 when Gaspard Tournachon took an oblique photograph of a small village near Paris from a balloon (Steven M. De Jong & Van der Meer, 2004). During the Civil War in the United States, aerial photography from balloons had a significant role (Steven M. De Jong & Van der Meer, 2004). From 1950 to 1970, remote sensing applications in urban context used film-based systems. During this period three main areas of interest were studied: early in the 1950s, researchers looked at urban land use and dynamics of housing and industrial elements; late in the 1950s, they looked at mapping, evaluation, and planning of urban transportation systems; and late in the 1950s, they looked at mapping density and quality of residential units, including environmental health conditions (1960s) (Rashed & Jürgens, 2010). Satellites have been monitoring earth's atmosphere since 1960 but no application to terrain information was done until the mid-1960s (Manolakis et al., 2016). In the early 1970s the National Aeronautics and Space Administration (NASA) launched the first Earth Resources Technology Satellite (which later became Landsat), designed to collect data from the earth's surface and its resources (Steven M. De Jong & Van der Meer, 2004; Navalgund, 2015). From the 1970s to the 1980s remote sensing imagery started to gain popularity in different fields such as ecosystems, resources, environments, human settlements and applications of impervious surfaces (Weng, 2012). The absence of appropriate sensors for detecting various types of impervious surfaces limited the number of studies on remote sensing of impervious surfaces in the 1990s. The study of paved surfaces became one of the most active areas in remote sensing in the twenty-first century (Weng, 2012), due to the increase in urban developments, since these surfaces represent the major contribution to environmental impact (Arnold & Gibbons, 1996) such as water quality and change in the hydrologic system (Schulte & Richards, 1996). With the evolution of technology, several satellites have been launched, spectrometers have improved, and hyperspectral sensors have been developed (Navalgund, 2015).

1.5.1 Remote sensors characteristics

Remote sensing technology provides a considerable application in a wide range of environmental disciplines such as geology, agriculture, geography, meteorology, oceanography, and geomorphology (Ben-Dor et al., 2001; Miller & Small, 2003).

RS acquire data from the energy emitted and/or reflected electromagnetic by surfaces. Then, these data are analyzed to provide information. RS needs a platform, either spaceborne or airborne, from which data are collected. Examples of satellite sensors are Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Ikonos, or Landsat. Airborne platforms can be airplanes or helicopters that hold RS sensors such as Airborne Visual and Infra-Red Imaging Spectrometer (AVIRIS), Compact Airborne Spectral Imager (CASI) or HyMAp (Borengasser et al., 2008).

Figure 1.4 illustrates the processes and elements involved in electromagnetic RS. There are five elements of data acquisition process: energy source (1), propagation of energy (2), energy interactions with the surface (3), retransmission of energy (4) and recorded energy by a remote sensor (5). Data analysis process comprises the analysis of the captured data using different viewing, computing and interpretation devices in a manual or automatic, visual, or digital way. In this phase, reference data concerning surfaces under study are used (if available) to assist the analysis process (6). Different processes can be applied by the analyst to extract information from the data collected by sensors. Then, this information is compiled (7) in maps or tables that can be merged with other layers using a GIS. Information can be presented to users (8) using a public dataset for decision-making process (Lillesand et al., 2015).

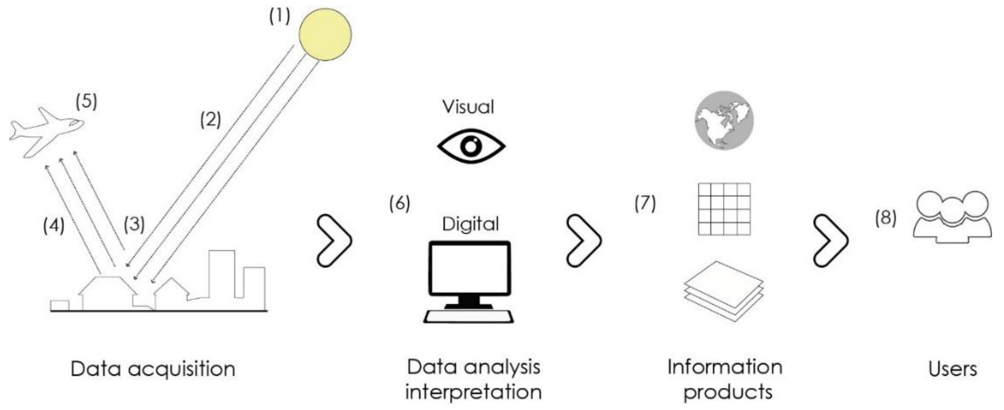

Figure 1.4. General processes and elements involved in electromagnetic RS. Energy source (1), propagation of energy (2), energy interactions with the surface (3), retransmission of energy (4), recorded energy by a remote sensor (5), data analysis process.

Figure 1.5 shows the classification of sensors and their main characteristics. Sensors can be classified into two general types: passive and active sensors. Passive ones depend on an external source of energy (usually the sun). These systems record electromagnetic energy reflected or emitted by surfaces under study. Examples of passive sensors are radiometers, spectrometers, or spectroradiometers (Jong et al., 2004). Active sensors record the radiation emitted by the sensor and reflected by the surface. An active energy source can be a lamp, a laser, or a microwave transmitter. Some examples are sound navigation and ranging (sonar), radio detection and ranging (radar), or light detection and ranging (LiDAR) (Konecny, 2014).

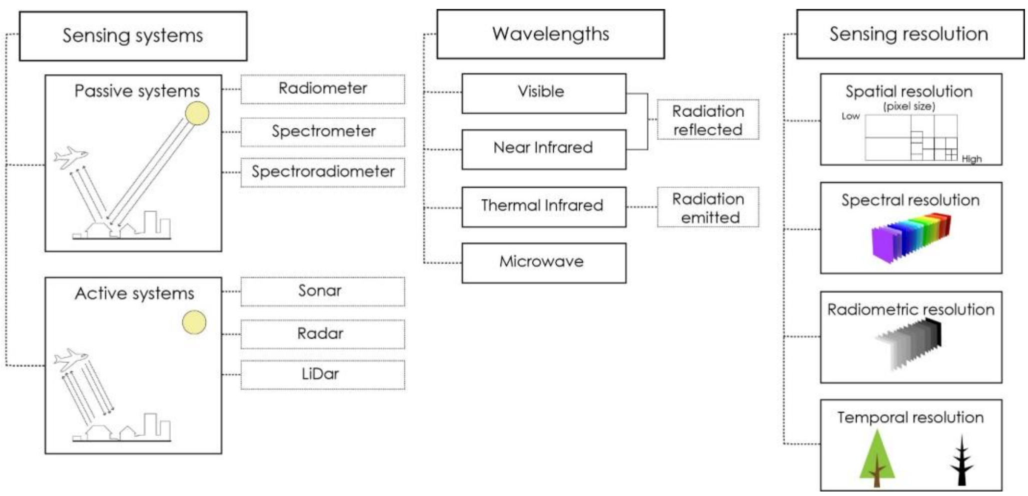

Figure 1.5. Classification of remote sensors and their main characteristics.

Wavelength

RS involves the measurement of energy in different parts of the electromagnetic spectrum. Major regions of interest are visible (VIS) from 380 to 780 nm, near-infrared (NIR) from 780 to 1 μm, shortwave infrared (SWIR) from 1 to 8 μm, and thermal infrared (TIR) from 8 to 14 μm (Konecny, 2014). All these regions are defined over atmospheric "windows" where this radiation is not greatly absorbed or attenuated by the atmosphere constituents.

The composition of every surface can be characterized by singular traits in its reflection/emission spectra, corresponding to different spectral regions depending on the physical processes involved in its interaction with radiation.

RS in the microwave and radio frequency region of the spectrum mainly provide primarily provide data about the object's physical and electrical attributes instead of its chemical qualities, which are provide in the visible/infrared region, or its thermal characteristics, which are the main contributors in the TIR and upper microwave regions (Elachi & Zyl Van, 2006). The green, red and NIR wavelengths give excellent possibilities to measure earth surfaces. TIR regions have proven to be useful in several geological applications and are also useful for monitoring the spatial distribution of heat from industrial activity and a variety of other applications such as fire and animal monitoring distribution. Microwaves regions offer the significant advantage of being used at night and in regions of persistent cloud cover (Eastman, 2001). Table 1.1 shows spectral regions and examples of remote sensing applications.

Table 1.1. Spectral regions and examples of remote sensing applications based on Elachi & Zyl Van (2006).

Spectral region	Examples of remote sensing applications
Gamma rays, x-rays	Mapping of radioactive materials
Ultraviolet	Presence of helium in atmospheres
Visible and near infrared	Surface chemical composition, vegetation cover, and biological properties
Mid-infrared	Surface chemical composition, atmospheric chemical composition
Thermal infrared	Surface heat capacity, Surface temperature, atmospheric temperature, atmospheric and surface constituents
Microwave	Atmospheric constituents, Surface temperature, surface physical properties, atmospheric precipitation
Radio frequency	Surface physical properties, subsurface sounding, ionospheric sounding

Spatial resolution

Spatial resolution (SR) is one of the most important requirements for detecting urban characteristics from remotely sensed imagery (Jensen & Cowen, 1999). This attribute refers to the size of the region on the surface that is summarized in a data value in the collected images. The first-generation satellites were able to acquire images with moderate SR (1 km to 100 m); for example, the Landsat MSS launched in 1972, which had a low SR of 80 m of pixel size. The second-generation satellites, increased SR (from 30 to 10 m), such as Landsat Thematic Mapper (TM) launched in 1984, that had a medium SR of 30 m. It allowed more detailed studies of urban environment. However, generally, sensors with medium SR are not sufficient to discriminate individual characteristics from urban contexts such as buildings, streets, or trees. The third-generation satellites are characterized by high SR (from 5 to 0.5 m or less), such as IKONOS (1999), QuickBird (2001), or WorldView 1 (2007) which have a SR of 1, 0.60, and 0.5 m respectively. High SR allows the acquisition of further spatial details and detailed-scale applications. Most high-resolution images have a low-spectral resolution (typically just four bands: blue, green, red, and NIR) and this makes difficult the discrimination of several urban covers with similar behaviors in this narrow spectral range, abundant in urban areas (Kadhim et al., 2016; Purkis & Klemas, 2013; Xian, 2016).

Spectral resolution

Spectral resolution refers to the number of spectral bands, their bandwidths, and their location along the electromagnetic spectrum that RS detects (Eastman, 2001). Most satellite sensors are multispectral systems such as Landsat, MODIS or ASTER. These systems characterize surfaces capturing only a few broad spectral bands. Imaging spectrometers also called hyperspectral remote sensors are sensors that are capable to acquire many spectral bands with narrow bandwidths. However, until very recently, most of this technology is limited to airborne or ground-based systems (Rashed & Jürgens, 2010). Data acquired from multispectral imagery commonly consist of 3 to 7 bands (e.g., Landsat satellite) of data and has bandwidths ranging from 50 to 120 or more nanometers (Lillesand et al., 2015). Imaging spectrometers are a revolutionary development in the progress of imagery systems. These systems have approximately 100 to 200 or more spectral bands with relatively narrow bandwidths (5-10 nm) across the VIS, NIR, SWIR, and TIR ranges of the electromagnetic spectrum (Liu & Mason, 2009; Helmi Z M Shafri et al., 2012).

Radiometric resolution

Radiometric resolution is determined by the detector in which radiance measurements are digitized and stored as digital numbers (DNs). Most of RS have quantization levels ranging between 8-bits (256 grey levels) and 12-bits (4 096 grey levels). For a successful analysis of remotely sensed imagery enough radiometric resolution is needed. Low radiometric resolution can be susceptible to saturation that results in deficient discrimination of urban environment features due to insufficient contrast (Jensen & Cowen, 1999). The Landsat multispectral scanner system used a 6-bit quantization level. The quantization level of most imaging systems such as Landsat TM, IKONOS, ASTER, or QuickBird is generally between 8-bit and 12-bit (Kadhim et al., 2016).

Temporal resolution

Temporal resolution refers to the theoretical or operational capability for acquiring repetitive imagery of the same place over some time interval. Platform attributes are the main factor that influences the theoretical and temporal resolution. Aircrafts are more agile than spaceborne platforms and provide the potential for temporal resolutions of a few minutes. Most spaceborne systems use polar-orbiting constellations of satellites with the limitation of repeating the capture in a range from days to weeks. Viewing swath also influences temporal resolution. Larger viewing swath allows monitoring the Earth's surface in shorter time periods (Rashed & Jürgens, 2010).

1.5.2 Roofs characteristics and remote sensing

Roofs represent half of total impervious surface in cities and generally are unused spaces. However, in the last years, many projects showed the potential of rooftops for producing resources. These areas can be used for growing food, collecting water, and generating energy (e.g., solar photovoltaic or solar thermal panels). To assess and integrate urban agriculture, rainwater harvesting and solar panels systems, roof characteristics such as geometry, area, slope, solar radiation, and construction material are needed (Carter & Keeler, 2008; Orsini et al., 2016; Toboso-Chavero et al., 2018; Villarreal & Dixon, 2005).

Roof information has traditionally been conducted through existing databases and ground-level measurement techniques. However, these techniques are inefficient, time-consuming, and impractical for obtaining roof information on a large basis. In this sense, new methods are needed to obtain roof information properties, and RS technology represents an efficient and advantageous tool to obtain information at large scales about impervious surfaces such as roads, sidewalks, and roofs (Samsudin et al., 2016).

LiDAR systems

LiDAR systems are active RS devices that focus on geometry rather than radiometry (Weng, 2012). These sensors have been used to create digital elevation models (DEMs) and digital surface models (DSMs) (Wang & Wang, 2011). LiDAR technology can provide precise information about elements in an urban area such as buildings and trees (Martín et al., 2015). LiDAR data have shown great potential in building and road extraction. Due to its high data resolution, fast processing time and low cost, this type of sensor is becoming more and more popular.

LiDAR and UA. Berger (2013) analyzed the potential of RUA in New York City using LiDAR data. These data allowed the identification of roof characteristics such as surface area and slope to assess the feasibility of integrating RUA systems. Saha and Eckelman (2017) described an automated procedure combining GIS and LiDAR data to quantify suitable areas for UA at ground level and on rooftops, a digital surface model (DSM) of Boston buildings was created using a remotely sensed LiDAR point-cloud dataset, from the DSM the roof area and slope were obtained to identify potential roof areas for UA. Nadal et al. (2017) used LiDAR data obtained with a Leica ALS50-II airborne sensor, roof characteristics such as area, solar radiation, and slope were obtained; these data allowed the identification and assessment of roof potential to integrate UA in industrial buildings in Barcelona, Spain.

LiDAR and RWHS. Grant, McKinney, and Ries (2017) used LiDAR data to identify rooftop surfaces, LiDAR data allowed calculation of catchment area of rooftops and the potential for RWHS in Florida (USA). Lupia et al. (2017) analyzed the water savings through RWHS from building rooftops to irrigate fruit and vegetable crops in the urban area of Rome, Italy, information of rooftops areas were obtained from LiDAR data, and then the total roof surface was analyzed to quantify rainwater collection. Oyedayo (2018) provided a novel framework for understanding the spatiotemporal pattern of rooftop rainwater harvesting potential in the Taita Hills region (Kenia), providing decision support for RWHS implementation. In this case, LiDAR data recorded by Leica ALS60 sensor were used to automatically generate roof polygons and to estimate the rooftop rainwater harvesting potential for domestic water needs in the region.

LiDAR and PV. Several works used GIS and remote sensing LiDAR data to quantify solar PV potential on roofs (Palmer et al., 2018). Margolis et al. (2017) used LiDAR data to estimate the shading, tilt, and azimuth of rooftops. A series of criteria were then applied to determine whether the roof surfaces were suitable for PV systems. Nguyen et al. (2012) assessed PV rooftop solar potential in Kingston (Canada) using a LiDAR Optech Airborne Laser Terrain Mapper 3100, potential rooftops suitable for PV systems were identified and a calculation of the total potential area was performed. Brito et al. (2012) estimated the PV roof potential in

Carnaxide (Portugal) using building footprints from LiDAR data. Kodysh, Omitaomu, Bhaduri, & Neish, (2013) estimated the solar potential on rooftops in Knox County, Tennessee (USA). The study allows the identification of suitable roofs with higher potentials for installing PV systems. (Bayrakci Boz et al., 2015) acquired LiDAR data and building footprints to obtain roof characteristics (slope, azimuth, and shading) to identify rooftops suitable for solar energy systems in the city of Philadelphia (USA).

Through the previous review, we can observe that to assess the feasibility of rooftop UA, all studies obtained roof area and slope data from LiDAR to identify minimum surface requirements and presence of flat roofs. To identify suitable areas for RWHS LiDAR data were used to identified and quantify roof areas in these cases, roof areas were utilized to estimate the total amount of rainwater that can be harvesting. In contrast to the previous areas of application (UA and RWHS), the use of LiDAR data has been widely used for PV potential, geometric data of the roofs, such as area, slope, and azimuth, were used to identify and calculate solar potential.

All these works identified geometric roof characteristics (slope and surface area), shadows and solar access, which are essential roof properties to assess the potential integration of FWE systems. However, LiDAR technology does not have the capability to identify roof materials.

Imagery systems

Urban areas constitute a complex mosaic of materials given the diversity of land use and cover types. Hyperspectral imagery provides data to discriminate between spectrally similar materials, usually present in urban environments (Heiden et al., 2007; Priem & Canters, 2016; Wang et al., 2016). Hyperspectral imagery provides high spectral and spatial resolution; therefore, a detailed pixel spectrum is available, with much more information about surfaces than the one in multispectral imagery (Heiden et al., 2012).

Imaging systems and UA. Nadal et al. (2017) used hyperspectral data acquired from a Thermal Airborne Spectrographic Imager 600 (TASI-600) to identify the following roof materials: metal, gravel, concrete, and fiber cement, data were used to evaluate the possible installation of rooftop greenhouses for growing food in Barcelona, Spain. Nadal et al. (2019) used orthoimages from a satellite to assess UA potential on residential buildings in Quito, Ecuador.

Imaging systems and RWHS. Ojwang et al. (2017)used HSR imagery (WorldView-2 satellite) to detect roof areas and materials to integrate RWHS in Mombasa (Kenya). Roof materials such as tiles, iron, and concrete were detected using supervised image classification, and a total roof area of 3 km^2 was identified as suitable for RWHS. Radzali et al. (2018) used WorldView-3 satellite imagery to acquire spatial and spectral measurements of rooftops, three types of roofing material were identified in the study area: concrete, metal, and asbestos; in addition, the condition (new or old) of the roof was identified. This assessment was done by the true color combination of bands 5, 3, and 2 of the WorldView-3 images, the results allowed the identification and quantification of roofs to integrate RWH in Seri Kembangan, Malaysia.

Imaging systems and PV. Jamal et al. (2014) mapped the solar potential on roofs available in Dhaka (Bangladesh) and evaluated the possible electricity supply from rooftop PV systems. To perform the estimation, Quickbird satellite imagery was used. Singh and Banerjee (2015) used a combination of land use information and GIS-based satellite imagery analysis for evaluation of rooftop PV potential in Mumbai (India). Khan & Arsalan (2016) used satellite imagery acquired from Google Earth™ to identify the available rooftop areas for PV potential, the case study was performed in Karachi (Pakistan).

As we can observe, imagery systems have rarely been used to identify roof properties for UA implementation purposes. However, through these systems, it is possible to obtain roof material information for integrating UA rooftops essential data for this purpose. Few works have used imagery systems to obtain information on roofing materials and roofing conditions to assess the potential of RWHS. However, most of the studies used imagery systems to identify roof areas without considering roof materials. There have been many studies conducted by different researchers around the globe that demonstrated the use of RS data (multi- or hyperspectral) for the identification and estimation of rooftop PV potential (J. Khan & Arsalan, 2016). However, there is no research about the identification of roof materials with the purpose of assessing the feasibility of PV systems.

In conclusion, hyperspectral data obtained by imaging spectrometers offers opportunity to obtain comprehensive information on the characteristics of a variety of surface materials. (Arnold & Gibbons, 1996). In contrast to LiDAR systems, that provide information about the height and geometric properties of roofs. High-resolution images can provide information about spectral signatures and hence, roof composition.

The output from RS can be in various forms and generally the information is used as input in analyzing and interpreting data using GIS. Information stored in GIS can be combined with other types of information for various studies or applications by combining different spatial data (Jong et al., 2004).

Most of the works developed to identify roofs characteristics for integrate FWE systems, centers their interest in the slope, surface area, shadows, and solar access. However, roof material is essential data. If the roof does not have the necessary load-bearing, which is essential to support the weight of FWE systems. Additionally, roofing materials have a major impact on the quality and amount of rainfall collected on rooftops (Farreny et al., 2011; Nadal et al., 2017; Sanyé-Mengual et al., 2015a).

1.6 Geographic information systems

GIS are computer systems for capturing, storing, analyzing, and displaying geospatial data and is composed of software, hardware, data, and users. The beginning of GIS in its current form is due to the fast development in computing tools in different fields such environmental, land management, and urban planning. The first GIS was developed by Roger Tomlinson in 60s who created the first Canada Land Inventory for the Agricultural Research Development Agency (Chang, 2018; Konecny, 2014).

GIS has been important in transportation, health care, public services, agricultural applications, water resources, ecology and archeology applications or urban planning, among others. In addition, it has become an essential tool for governments and to support decision-making processes at urban scales, and involves interdisciplinary fields: cartography, for the automation of the manual mapping process by replacing drawing work with vector digitalization; computer graphics, for the applications of digital vector information other than cartography; databases, whose mathematical structure allows the handling of computer graphics and mapping; and remote sensing, which generates enormous quantities of digital imagery information (K. Chang, 2018; Konecny, 2014). These systems are capable of storing both locational and attribute data associated with localization data (Lillesand et al., 2015). A major advantages of a GIS is the capability to interrelate spatially different types of data from multiple databases.

1.7 Motivations of the dissertation

Rooftops represent potential spaces in cities for integrating systems that can supply food, water, and energy to citizens. There are some works that assess the potential integration of UA, RWHS, and PV systems. Nevertheless, most of the existing works consider them as isolated only one system. Regarding FWE nexus there is a lack of procedures to assess their integration in a holistic way. In addition, data about materials, geometry and solar access are required; the main challenge is the access to this information, a defined framework and scale up the assessment of feasible roofs. Remote sensors technology has been typically used to detect land use, urban growth, and individual objects. This technology can also assist the characterization of roofs. Some works exist regarding spectral characteristics of roofs. However, there is a need for spectral knowledge regarding the use of high spatial resolution remote sensing to acquire spectral data according to each specific geographic region.

The production of resources in cities contributes to environmental, social, and economic benefits. The assessment of food, water, and energy self–sufficiency can contribute to urban sustainability and provide data for promoting the integration of FWE systems on rooftops.

Most of RUA initiatives developed in Europe are taken by citizens for promoting production of local food and develop social cohesion and by research groups for technology development and agronomic experiments (Juniawati & Hayuningtyas, 2017). Few cities, for example, Paris, Copenhagen, and Berlin are promoting and have developed general guidelines and urban / building regulations. Some works in Southern Europe have been conducted to identify barriers and opportunities (Sanyé-Mengual et al., 2016) to support the integration of urban agriculture system on rooftops. Nevertheless, there is still a lack of information, about policies, factors, barriers, and opportunities to support RUA specially in the Southern Europe region, where incentives to support RUA projects have recently emerged. It is necessary to identify the elements mentioned above, as well as the stage of RUA project process are presented, their relevance and how often barriers are present, from the perception and experience of stakeholders, to understand and contribute to develop a solid basis for the city policies regulations to support RUA integration. This thesis aims to contribute to close these gaps and to improve the knowledge regarding cities and the production of local resources: food, water, and energy.

1.8 Objectives of the dissertation

The general research question of this thesis was as follow:

What are the required phases and the most viable approach using remote sensing technology to assess the potential of roofs for integrating food, water, and energy systems?

Question 1: What are the steps to acquire spectral data from roof materials at laboratory-scale and what are the spectral characteristics of these materials?

Question 2: Are hyperspectral remote sensing a reliable tool to identify roof materials in cities?

Question 3: What approach is most suitable to identify and quantify the feasibility of rooftops to integrate urban agriculture (RTGs and open-air), rainwater harvesting, and solar energy systems in residential and non-residential urban areas?

Question 4: Which are the key factors, legal constraints, barriers, opportunities and their perceived effect on RUA diffusion and in which scale and project's life cycle stage are presented?

The main goal of this dissertation was:

To establish the stages of the procedure for assessing the potential integration of urban agriculture, rainwater harvesting, and solar energy systems on rooftops, from a holistic perspective using remote sensing technology as well as social aspects. To address this objective, the following specific objectives were defined:

Objective 1: To contribute to the knowledge of spectral characteristics of roof materials by describing a framework for laboratory-based spectral (VIS-NIR) data acquisition and developing a spectral library of common roof materials and representative from the Mediterranean urban region (Chapter 3).

Objective 2: To identify and validate roof materials classes in a Mediterranean urban region (Chapter 4).

Objective 3: To assess the self-sufficiency of the integration of urban agriculture, rainwater harvesting systems, and solar energy systems on rooftops through the establishment and application of a framework to identify and quantify the feasibility of rooftops to integrate urban agriculture (RTGs and open-air) in residential and non-residential urban areas in a Mediterranean urban region (Chapter 5).

Objective 4: To provide an overview from a stakeholder's perspective of potential key factors, policies, and barriers associated whit the integrations of rooftop urban agriculture in European cities (Chapter 6 and 7).

Chapter 2

Materials and general methods

CHAPTER 2 - Materials and general methods

This chapter introduces the methodological framework applied in this doctoral thesis and lists the equipment and materials used. Methods and materials are specific to each chapter and are detailly described in the corresponding chapter.

2.1 Methods overview

Figure 2.1 shows an overview of the methods used, data acquisition tools, scale, and related disciplines in each study related to the chapters developed in this thesis. Since the thesis focuses on the study between cities and food, water, and energy resources a multidisciplinary approach was proposed to address this research. Methods include remote sensing, geographic, and social tools. Regarding data acquisition, each chapter was developed using different data acquisition tools, besides, in some chapters, various tools were used. Three different scales were proposed to develop the thesis: laboratory, building, and urban.

To perform **Chapter 3**, VIS-NIR remote sensor technology was used at laboratory scale to characterize roof materials. **Chapter 4** develops the process for mapping roof materials in cities. This study was developed using VIS-NIR, LWIR, and LiDAR remote sensing systems and GIS tools to identify and classify roof materials; it was developed at building and urban scales; architectural, urban planning, and environmental disciplines were involved in this chapter. **Chapter 5** describes a framework for assessing the feasibility of roofs to integrate RUA including RTGs and open-air systems; RWH; and PV systems on rooftops. This chapter was developed using results from **Chapter 4** and incorporating, datasets, and GIS tools; building and urban scales were included in this chapter; agricultural, architectural, urban planning, and environmental disciplines were considered. **Chapter 6** provides an overview of potential key factors, policies, and barriers associated whit the integrations of RUA in four European cities, Barcelona, Berlin, Bologna, and Paris from a stakeholder's perspective. This work was developed in two pashes, first, it was carried a workshop with international stakeholders, in the second phase, a survey was developed and provided to stakeholders from Barcelona, Berlin, Bologna, and Paris. Building and urban scales were considered in the questions. Finally, in **Chapter 7**, the world café method was used to identify potential social, environmental, legal/administrative, technological/architectural, and economic barriers and opportunities for the implementation of urban agri-green roofs; to determine the scale, including building, city, or global aspects, of potential barriers and opportunities; and to classify the perceptions of potential barriers and opportunities within a UAGR project's life cycle stages: project-construction-use in Barcelona.

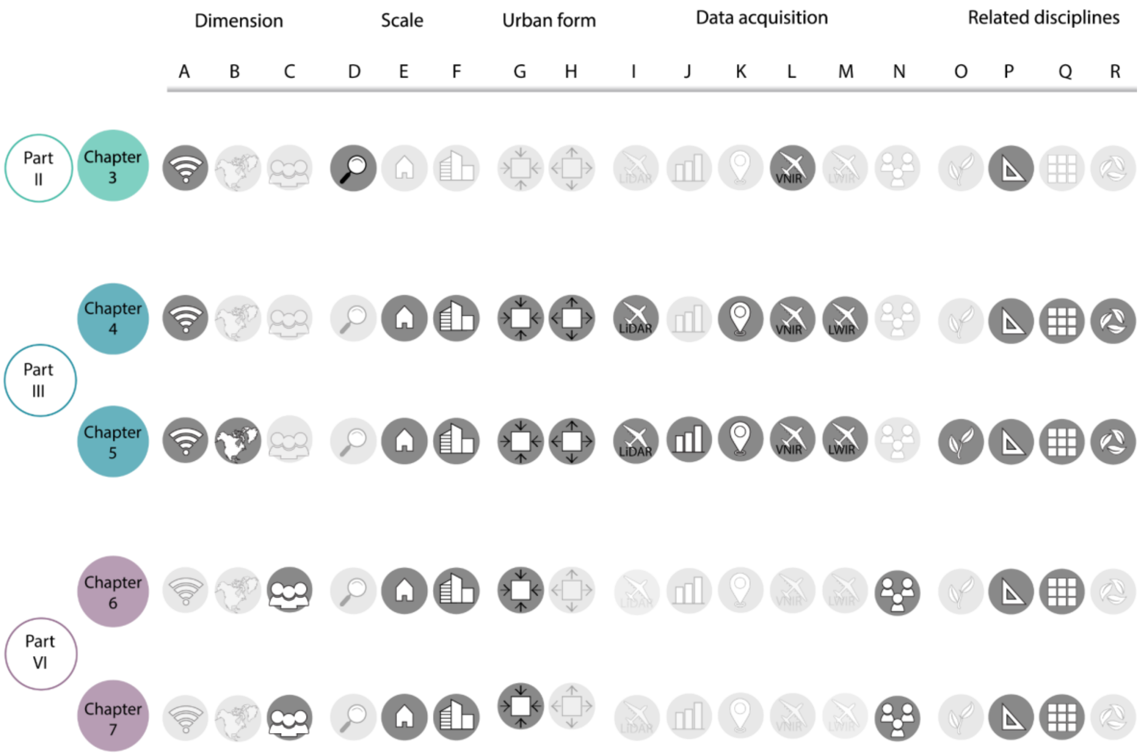

Figure 2.1. Overview of the methods. Dimension: (A) technological, (B) environmental, (C) social. Scales: (D) laboratory, (E) building, and (F) urban. Urban form: (G) compact, (H) diffuse. Tools for data acquisition: (I) LiDAR airborne sensor, (J) dataset, (K) geographic information systems, (L) VNIR airborne sensor, (M) LWIR airborne sensor, and (N) participatory process. Related disciplines (O) agricultural, (P) architectural, (Q) urban planning, and (R) environmental.

2.2 Remote sensing

The capacity to choose particular and numerous narrow wavebands that effectively distinguish urban surface materials is a significant benefit of hyperspectral image data over multispectral image data (Rashed & Jürgens, 2010). The tendency to achieve finer spatial resolution is demanded by specific applications that demand high spatial resolution data for city-related issues. (Xian, 2016). Three airborne sensors were used in this thesis, two passive and one active. Figure 2.2 shows spectral ranges that cover passive airborne sensors provided by the ICGC.

- The System for Different Applications (AISA) Eagle II manufactured by Specim, is a hyperspectral imager and covers the visible and near-infrared (VNIR) spectral range (Chapters 3, 4, and 5).

- The Thermal Airborne Spectrographic Imager 600 (TASI-600), manufactured by Innovation, Technology, Research, Excellence, and Science (ITRES), is a hyperspectral imager and covers the long-wavelength infrared (LWIR) spectral range (Chapters 4 and 5).

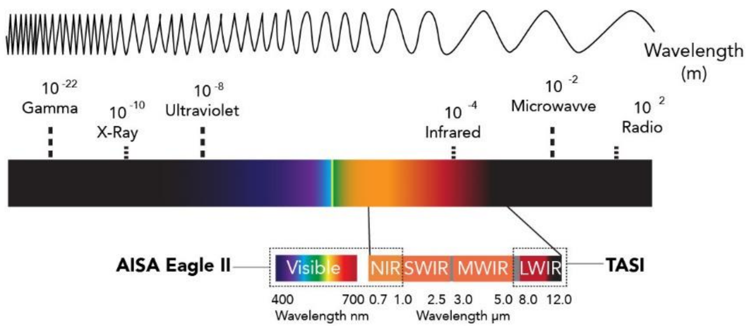

Figure 2.2. Spectral ranges that cover the passive remote sensors used in this thesis.

Active remote sensor:

- LiDAR system Leica ALS50-II manufacture by Leica Geosystems, the system computes this data using laser range and return signal intensity measurements (chapters 4 and 5).

2.2.1 Laboratory-based scale

Figure 2.3 shows the general framework to obtain spectral signatures of roof materials and the compilation of the results into a spectral library, divided into five general phases (for more detailed information see Chapter 3):

1) Selection of roof materials. Roof materials in urban areas were selected according to the literature (Castellanos, 1996; Chueca, 2003; Farreny et al., 2011; Nadal et al., 2017; Schunck et al., 2003). In total, 39 samples were selected, including ceramics, concrete, fibber cement, metals, plastics, paints, stone, and wood, and various colours were considered in the sample's selection.

2) Spectral data acquisition. Spectral data was collected in the Hyperspectral Laboratory of the CGIC. The laboratory was isolated from natural light as well as artificial light sources from adjacent spaces. Remote sensor AISA Eagle II was used to record radiance data from roof materials.

3) Image data preprocessing. The AISA Eagle II sensor records HSR images and spectra in raw DNs. After data acquisition, DNs were converted to radiance values using a calibration protocol from the sensor manufacturing company. GeoView 2 software was also used to select valid pixels from the image recorded with the RS.

4) Processing the radiance data. The absolute spectral reflectance α_λ was calculated by dividing the sample material radiance $\gamma_{\lambda,\mathrm{sample}}$ by the reflectance panel (Spectralon®) $\gamma_{\lambda,\mathrm{reference}}$ and by including the spectral reflectance of the Spectralon® R_λ. See Chapter 3 Equation 3.1.

5) Spectral library. All the acquired spectral reflectance data were compiled into a PDF that includes specific information about each sample material, photographs, and spectral signatures. A file with the reflectance values from each material is also provided.

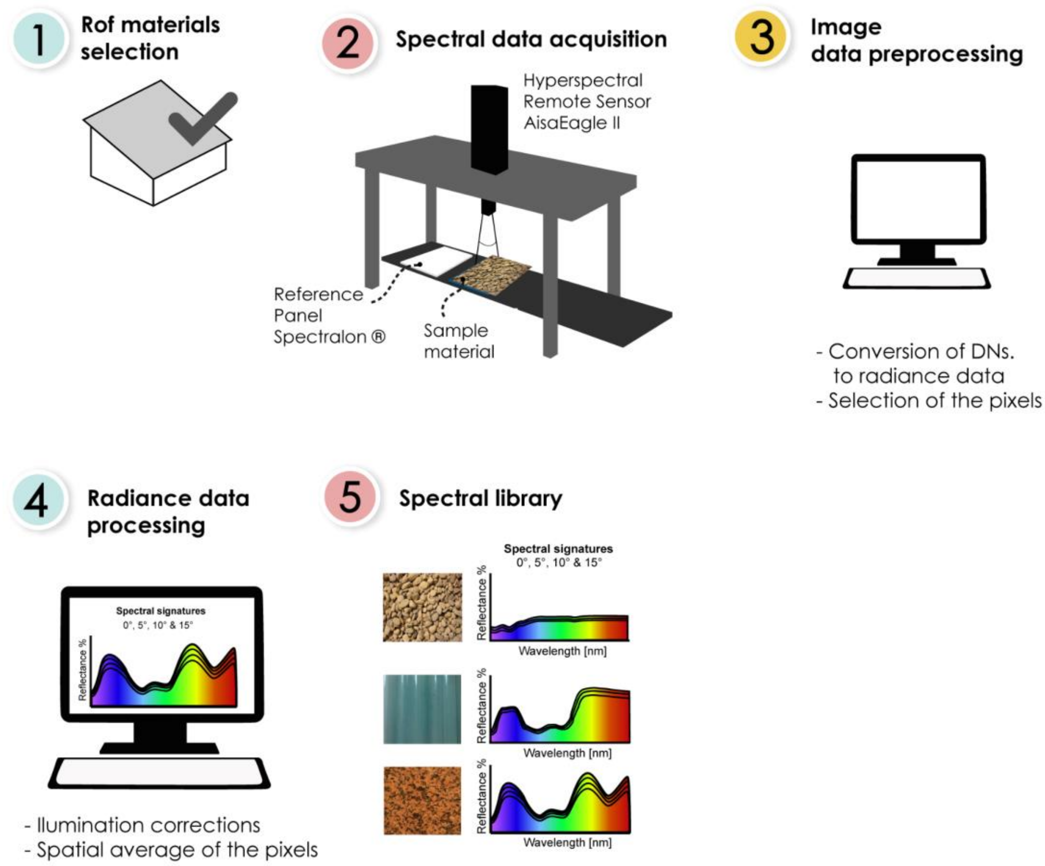

Figure 2.3. General diagram of the framework for laboratory-based spectral data acquisition of roof materials and the development of the spectral library.

2.2.2 Building and urban scale

Figure 2.4 shows the general framework performed in six general phases to map class materials of roofs in a Mediterranean urban area (for more detailed information see Chapter 4):

1) Data acquisition. Hyperspectral data from the study area were acquired with a flight conducted by the ICGC on March 6, 2018 at 11:35 AM local time, two hyperspectral airborne sensors were simultaneously operated AISA Eagle II and TASI-600. See Chapter 4, Table 4.2 for flight parameters and technical characteristics of the remote sensors.

2) Data preprocessing. It was made a mosaic of orthoimages with reflectance (VNIR spectrum) and emissivity (LWIR spectrum) values for each pixel in the images captured by HRS in the flight. Radiometric, geometric, and atmospheric corrections were performed in this phase using Environment for Visualizing Images (ENVI) software.

3) Data processing. This phase comprises a dimension reduction applying a maximum noise fraction (MNF) method and unsupervised classification of roofs applying a clustering algorithm (K-means), both processes were performed using ENVI software.

4) Roof polygon class assignment. The number of pixels in each roof polygon was computed and the majority class was set as roof polygon class this process was done using QGis and a DSM obtained from LiDAR data from a flight conducted in 2013 by the ICGC[1]. See Chapter 4 Table 4.3 for flight parameters and technical characteristics of LiDAR airborne sensor.

5) Accuracy assessment. A validation process was achieved using three different methods: (1) visual inspection, (2) information from field experts, and (3) field inspection. To validate the results of unsupervised classification, a quantitative accuracy assessment was performed by randomly selecting roof samples.

6) Quantitative feasibility analysis. To quantify the feasibility for integrating FWE systems, existent literature related to suitable roof materials for FWE production was used as a reference. Then, the total surface of each class in the study area was related to the suitable roof material for integrating each FWE system.

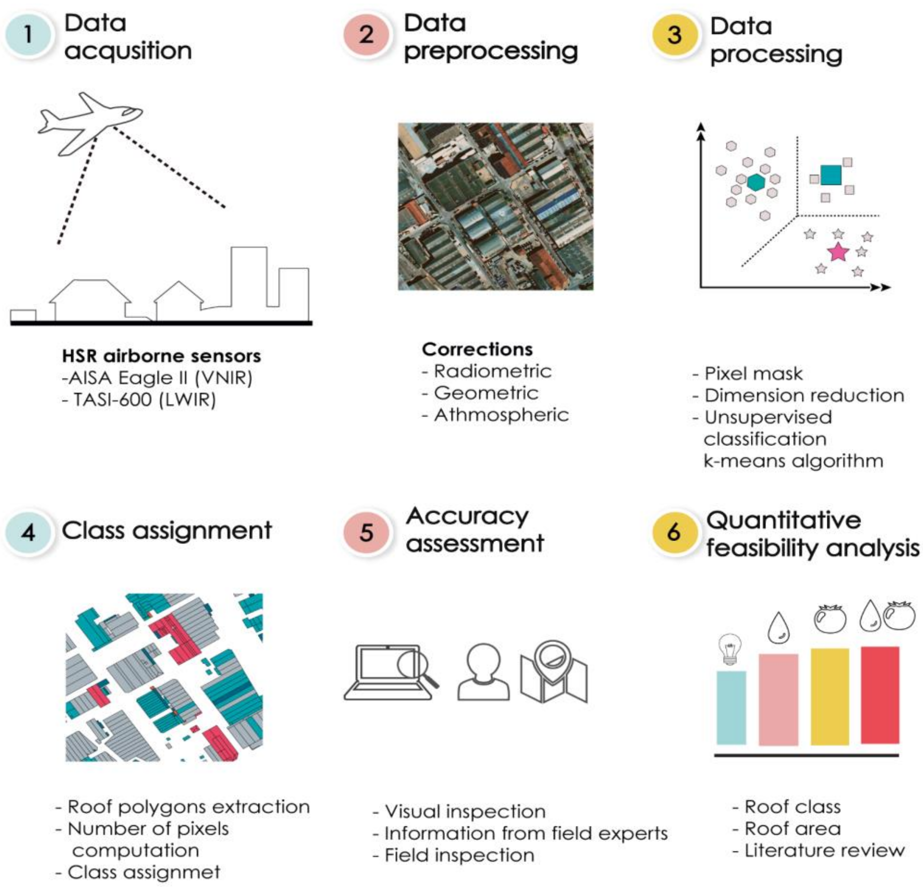

Figure 2.4. Diagram of the general workflow to classify roof materials from the Vallès Occidental case study.

[1] Flight performed in 2018 was specially designed to acquire data for this thesis. Flight performed in 2013 was not developed for this thesis, however, derived data of the flight were used. Both the 2018 hyperspectral flight and 2013 LiDAR data were possible due to a contract between the ICGC and UPC (Fertilecity II project (MINECO/FEDER, UE: CTM2016-75772-C3-1-R; CTM2016-75772-C3-3-R).

In Chapter 5, the work developed by Nadal et al. (2017) and Toboso-Chavero et al. (2018) were used as a basis to assess the feasibility of roof areas for integrating food production, rainwater collection, and solar energy systems in cities using remote sensing technologies and to evaluate the potential integration and self-sufficiency of FWE systems for commercial and non-profit purposes in a Mediterranean area. Figure 2.5 shows the workflow divided into four general phases to identify feasible roof areas in cities (for more detailed information see chapter 5):

1) Study area characterization. Data about the population was obtained from a public dataset. GIS was used to define the boundaries, identify roof area, land use and building typologies, for this purpose, two vector layers were used: (1) from The Urban Planning Map of Catalonia (UPMC) and (2) roof classification developed in this thesis.

2) Climatic conditions. Datasets from public web sites were used to obtain climatic conditions rainfall and solar radiation.

3) Urban and architectural requirements. To address legal requirements the Barcelona Metropolitan General Plan regulations and building codes (Metropolitan area of Barcelona, 2018) were consulted. Building uses were identified from the UPMC layers. Remote sensing technology was used to obtain geometric characteristics, solar radiation values, and a material class of roofs (obtained in Chapter 4). Data layers with roof characteristics were integrated into a single GIS layer with QGis software. Then, potential roofs for Integrating FWE systems were identified.

4) Self-sufficiency indicators. First, the production of food, water, and energy was calculated. Tomatoes and lettuce were considered as suitable crops due to household consumption data (Departament d'Agricultura Ramaderia, Pesca i Alimentació, 2017). The average yield values were calculated considering the systems and the methods of growing. To calculate the rainwater harvesting potential, different runoff coefficient were considered (Farreny et al., 2011). For PV was chosen multi-crystalline silicon (multi-Si), due to it is the most common in the market (Paiano, 2015). To determine the potential production of food, water, and energy the total feasible rooftop area (m^2) obtained from the previous phase and the Equations 5.1, 5.2, and 5.3 were used (see Chapter 5). Then, to determine the potential of self-sufficiency (# persons) food, water, and energy demand were calculated and Equations 5.4, 5.5, and 5.6 were applied (see Chapter 5).

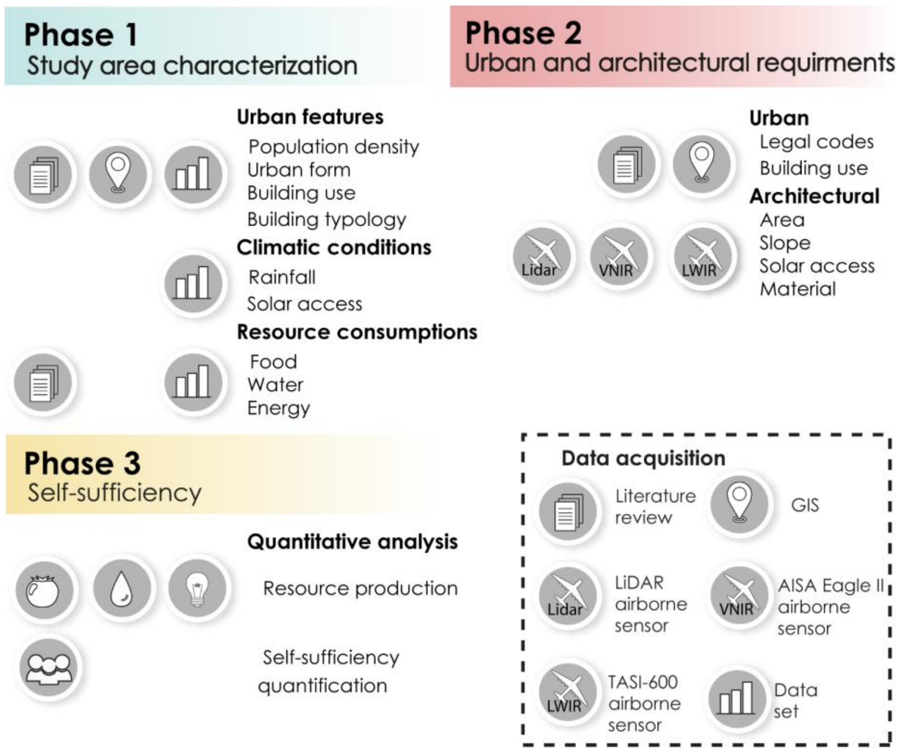

Figure 2.5. Workflow to assess the feasibility of roof to integrate food production, rainwater collection, and solar energy systems in cities.

2.3 Geographic tools

GIS was used to acquire, manage, and analyzed data as well as creating a dataset of roofs. The following software's were used: ENVI, QGis, GeoView 2, and GRASS 7.2. The use of these tools can be summarized in the following general stages (specific details are described in Chapters 3, 4, and 5):

- To generate spectral signatures and reflectance data of roof materials in Chapter 3 more detailed information is provided.
- To classify roof materials using hyperspectral image (acquired with airborne sensors), and a clustering algorithm (k-means), Chapter 4 provides detailed information.
- To process and perform the necessary corrections (radiometric, geometric, and atmospheric) of spectral and geometric data of roofs acquired with airborne sensors in the Vallès Occidental (Barcelona), chapter 4 provides detailed information.
- To identify roof polygons and to generate data regarding geometric characteristics of roofs acquired with airborne sensors in Chapter 5 more detailed information is provided.
- To characterize solar irradiation on roof surfaces considering all the shadowing effects in the surrounding area from the case study (see Chapter 5).
- To identify feasible roofs for integrating urban agriculture, rainwater harvesting, and photovoltaic systems in chapter 5 more detailed information is provided.

2.4 Social tools

Data collection was carried out through a workshop, a survey, and the World Café method.

2.4.1 Workshop and survey

In Chapter 6 an international workshop and a survey including open, closed, and Likert scale questions were used. Figure 2.6 shows the seven general steps to develop this work (for more detailed information see Chapter 6).

1) Case studies. Four cities from Europe Barcelona, Berlin, Bologna, and Paris, were chosen as a cases study due to these cities hosted RUA projects with the main purposes to social inclusion, technological development, and research.

2) Participant definition Phase 1. Persons involved in UA were identified and classified by categories: projects developers, public administrators, academics, and researchers.

3) Data collection Phase 1. To collect data from stakeholders a workshop was performed on ICTA-ICP building in September 2017. The workshop was developed in five steps.

4) Key factors and barriers definition. Key factors, potential policies, and barriers for integrating RUA were identified based on the results of the workshop and a literature review related to RUA.

5) Participant definition Phase 2. Experts involved in UA, projects developers, public administration, and academics from Barcelona, Berlin, Bologna, and Paris were identified to participate in the survey.

6) Data collection Phase 2. Was performed using an on-line survey divided into six sections: (a) survey description and context, (b) stakeholder information, (c) key issues for integrating RUA, (d) factors that hinder or promote RUA, (e) public policies to promote RUA, and (f) barriers for integrating RUA (for more detailed information see Supporting information 3.1).

7) Data analysis. A quantitative analysis from the result was performed to identified both global (total of answers) and local (by city) trends.

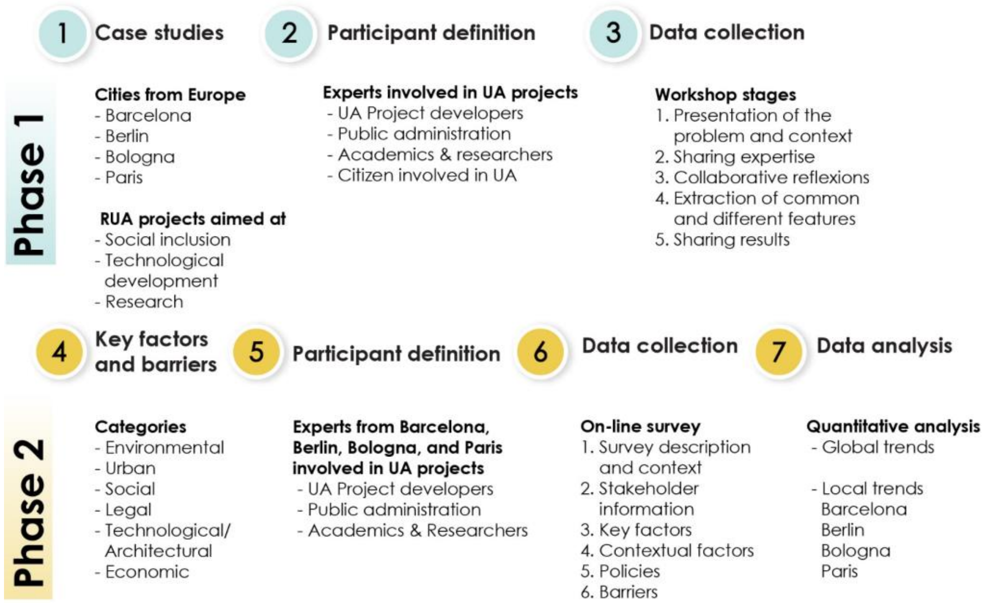

Figure 2.6. General framework for identifying key factors, policies and barriers for RUA diffusion based on stakeholder perceptions in four European cities.

2.4.2 World Café

Five stages were considered to identify perceived barriers and opportunities of agri-green roof projects implementation in Barcelona. Figure 2.7 shows the workflow used (for more detailed information see Chapter 7):

1) Case study. It was chosen the city of Barcelona according to different criteria. In this phase, a description of the location, context, boundaries, and kind of projects under study were described.

2) Participants' definition. Stakeholders involved in The First Green Roof Contest organized by Barcelona's city council were identified and invited to participate.

3) Identification of barriers and opportunities. Five categories (social, environmental, legal/administrative, technological/architectural, and economic) were identified according to the literature review (Cerón-Palma et al., 2012; Nadal et al., 2018; Sanyé-Mengual et al., 2016; Specht & Sanyé-Mengual, 2017).

4) Data collection. The World Café method was used to collect data, by applying the seven principles described below (The World Café Community Foundation, 2015).

5) Data analysis. Data generated from the discussion tables were thematically organized and analyzed in Microsoft Excel ®.

Figure 2.7. Summary of the workflow to identify potential barriers and opportunities regarding UAGR implementation.

The World Café method was chosen for data collection. According to the literature, this participatory method is particularly powerful due to the informal environment but with a structured dialogue that focuses on relevant questions to the participants and the rounds of information exchanges between the stakeholders, that results in a cross-pollination of ideas (Estacio & Karic, 2015; Fouché & Light, 2011). For addressing the World Café it was considered seven principles (The World Café Community Foundation, 2015) in the design implementation. Figure 2.8 shows the principles that were applied:

1) Set the context. This principle refers to the importance of defining the purpose and the parameters that are addressed to develop collaborative learning, for both preparing and during the participatory process.

2) Create a hospitable space. It is necessary to create a space of welcoming, in this sense, the selection of location, furniture, and catering services and the development of invitation, introduction to the process and communication during the process contribute to creating comfort and welcoming to the participants.

3) Explore questions that matter. A relevant question for the participants was addressed for each period, then a progressive deeper line was introduced by the hosts.

4) Encourage everyone's contributions. The host invited to develop the active participation of all participants and listen to their contributions.

5) Connect diverse perspectives. Table hosts summarized the conversation of the previous round for the new participants and invited them to share their opinions, also the host of each table contributed to connecting ideas from participants.

6) Listen together for patterns, insights, and deeper questions. It was encouraging to participants to listen to all the opinions.

7) Share collective discoveries. At the end of the session, the collective knowledge was displayed to all the participants.

Figure 2.8. Seven principles of the world café applied for design the participatory process. Adopted from Brown & Isaacs (2005).

2.5 Case studies

This thesis takes as case studies different locations:

(a) The Vallès Occidental (Chapters 4 and 5) region located north of Barcelona. Figure 2.9 shows the location and main characteristics of the study area. This region is comprised of 23 municipalities and is part of the Metropolitan Area of Barcelona (MAB). The AMB represents the seventh most populous city in the European Union (Eurostat, 2019). The study area comprises five municipalities, three of which are part of the MAB (Badia del Vallès, Barberà del Vallès, and Cerdanyola del Vallès) and two are not Sabadell and Santa Perpètua de la Mogoda. The total area of the case study is approximately 15 km^2 with compact and diffuse urban forms. In the Cerdanyola del Vallès municipality, a pilot RTG started to operate in 2014, the ICTA-IPC building, in the UAB campus (Fertilecity, 2018). This RTG focuses mainly on research and technological innovation fields.

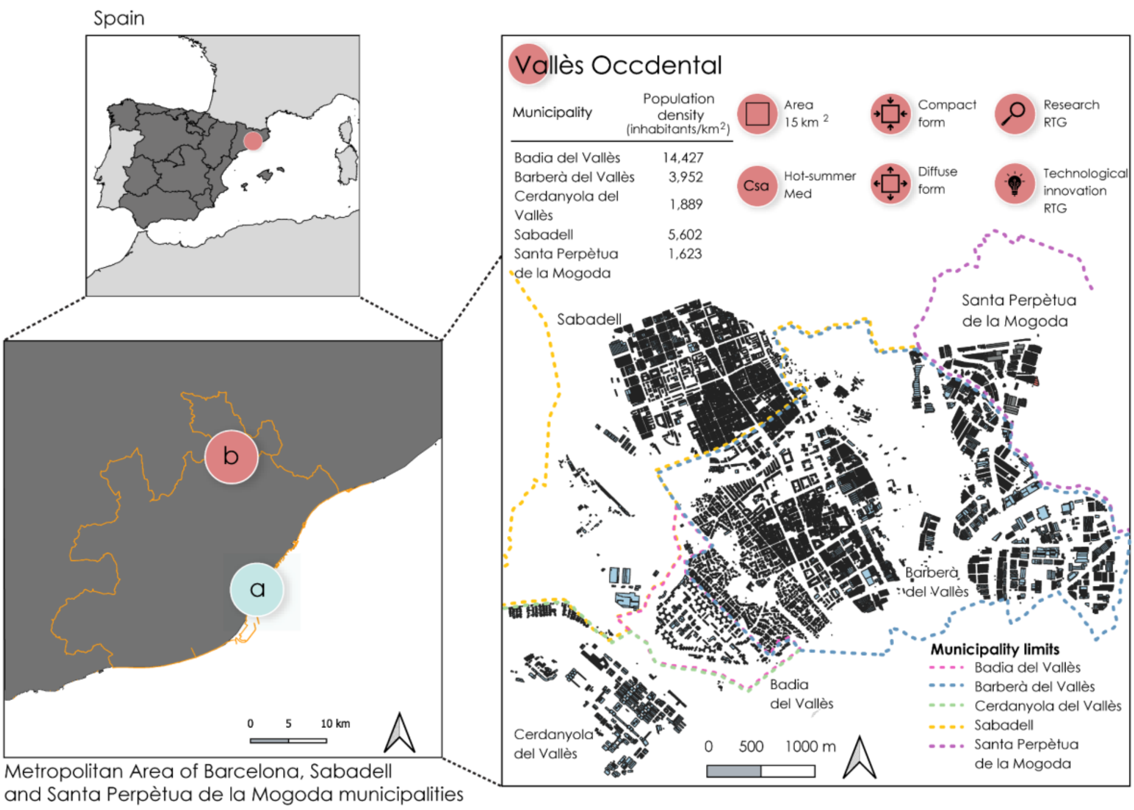

Figure 2.9. Summary of the main characteristics of case study located on the Vallès Occidental. Metropolitan area of Barcelona (a) and the Vallès Occidental region (b).

(b) Four cities from Europe, Barcelona (Chapter 6 and 7), Berlin, Bologna and Paris (Chapter 6). Figure 2.10 summary of the main characteristics of the case studies.

Barcelona is the capital of Catalonia (Spain), located on the northeastern coast of the Iberian Peninsula. According to Koppen's climate classification, this city is characterized by a hot-summer Mediterranean climate (Csa) (Mindata, 2021). Barcelona has 1.6 million inhabitants in 101 km^2, their population density is 16,420 inhabitants/km^2 (Statistical Institute of Catalonia, 2020) being among the densest and most compact municipalities in Europe (Barcelona City Council, 2018). This city, has a limited green space per capita, about 7 m^2/inhabitant in the city center (17,62 m^2/inhabitant if peri-urban park Collserola is included) (Medi Ambient i Serveis Urbans, 2013). The absence of land has prompted investigating better approaches to integrate agriculture in the city. It Has RUA projects focusing on social, research and technological innovation purposes in the city. In 2016 five rooftop gardens on municipal buildings were thanks to the initiative *L'Hort al terrat* (Garden on the roof) promoted by the City Council. Crops include lettuce, endive, spinach, chard, tomatoes, peas, zucchini, cucumbers, peppers, and different aromatic plants (Barcelona City Council, 2018b). Today, the objective of the Garden on the roof initiative is to install a total of ten rooftop areas for crop production in the city. This is also consistent with Barcelona's Climate Plan 2018-2030, which sets the promotion of productive roofs among the short-term actions (Barcelona City Council, 2018a). In 2017 the *Primer Concurs de Cobertes Verdes* (the First Green Roof Contest) was launched which included food production on roofs (Barcelona City Council, 2017). In addition, Barcelona will become the World Capital of Sustainable Food in 2021. Barcelona candidacy, therefore, has highlighted the Barcelona Food Policy Strategy 2016-2017 that the city has been developing in recent years and that it wants to develop in this new mandate (Barcelona City Council, 2020).

Berlin is the largest city and the capital of Germany, located in the north-east of Germany. The climate is temperate oceanic climate (Cfb) under the Koppen climate classification (Mindata, 2021). Berlin has 3.7 million inhabitants (Berlin business location center, 2019) who live over a surface of 892 km^2 (OECD, 2010). The average population density amounting to 4,147 inhabitants/km^2. Berlin has a compact urban forma and the green space per capita is 17 m^2/inhabitant (Baró et al., 2015). Considering the great metropolitan area Berlin is the fourth most populous city in the European Union with 5.1 million inhabitants (Eurostat, 2019). In recent years, commercial urban farming enterprises started to develop prototypes and technologies for ZFarming (a subtype of UA characterized by the non-use of farmland or open space) (Specht et al., 2016c). Recently, commercial urban agriculture companies have begun to develop technologies for ZFarming and city scale food production. (Specht et al., 2016c). Altmann et al. (2018) identified in Berlin a potential surface of about 890 ha available for RUA, suggesting that such vacant area could overcompensate the annual vegetable requirements of the city inhabitants. Accordingly, Berlin was suggested as a promising site to develop RUA projects (Specht et al., 2016c). Today, among existing RUA projects, two rooftop gardens with a social focus and one RTG located on the Humboldt University building with the main objective to be a research lab for botanical bachelors, master, and Ph.D. workgroups (Tao et al., 2020).

Bologna is the main province of the Emilia Romagna Region, situated in northcentral Italy, a post-industrial and compact metropolis (Carbonaro & Pancotti, 2019). This city, has a humid subtropical climate (Cfa) Koppen classification (Mindata, 2021). Bologna has 394,463 inhabitants, the city comprise an area of approximately 141 km^2 and has a population density of 2,802 inhabitants/km^2 (ISTAT, 2010, 2021). Green space per capita is about 14 m^2/inhabitant (Openpolis, 2018). In 2010 it was the first city to integrate RUA on public housing buildings. Three community rooftop gardens were installed on the 10th-floor of social housing buildings, within the project GreenHousing, partnered by the University of Bologna, the city Council, and the no-profit initiative BiodiverCity (Orsini et al., 2014). Bologna was then the first city to integrate RUA on public housing buildings in Europe (Orsini et al., 2014). The rooftop gardens hosted three cultivation systems: soil production with compost, floating hydroponic and a simplified nutrient film technique, where vegetable and aromatic crops were grown (Sanyé-Mengual et al., 2017). Bologna was also one of the first cities in Italy to introduce a local plan for adaptation to climate change. Greening strategies were proposed to address microclimate mitigation, also foreseeing the creation of 5 ha of urban vegetable gardens. It was estimated that vacant roofs of the city would account for about 82 ha and, when converted in RUA projects, they could potentially enable for an annual production of 12'495 t of vegetables year, about ¾ of the city vegetable requirement (Orsini et al., 2014).

Paris capital of France has 2.2 million of citizens, the city covers a surface of 105 km^2 and has one of the highest urban densities in the world up to 20, 755 inhabitants/km^2 (INSEE, 2017). Paris covers a small urban land area (Kamal Chaoui & Plouin, 2012), and characterizes European cities planned with a remarkable compactness and uniformity. (Chatzipoulka & Nikolopoulou, 2018). This city is characterized by a temperate oceanic climate (Cfb) according to Koppen classification (Mindata, 2021). Over the last years, Paris green space per capita was around 6 m²/inhabitant (Natura sciences, 2017). According to Paris Climate Action Plan (2019), the city is committed to supporting various UA and permaculture projects on open grounds and both on the walls and roofs of municipal buildings (City of Paris, 2018). In 2016 and 2017, the first and second editions of the Parisculteurs program were launched, targeting the creation of UA projects on buildings (Ville de Paris, 2019), as part of the "Objective 100 hectares", a municipal program that targeted the creation of 100 hectares of green roofs and walls, one-third of which devoted to UA by 2020 creating social inclusion and research spaces (Collé et al., 2018). Another initiative to promote UA is the 48h of urban agriculture, launched in Paris in 2016, is a multitude of participatory events open to the general public organized by local structures in more than 20 cities in France, Belgium, Spain and Switzerland with the aim of discovering urban agriculture (Les 48h de l'agriculture urbaine, 2020).

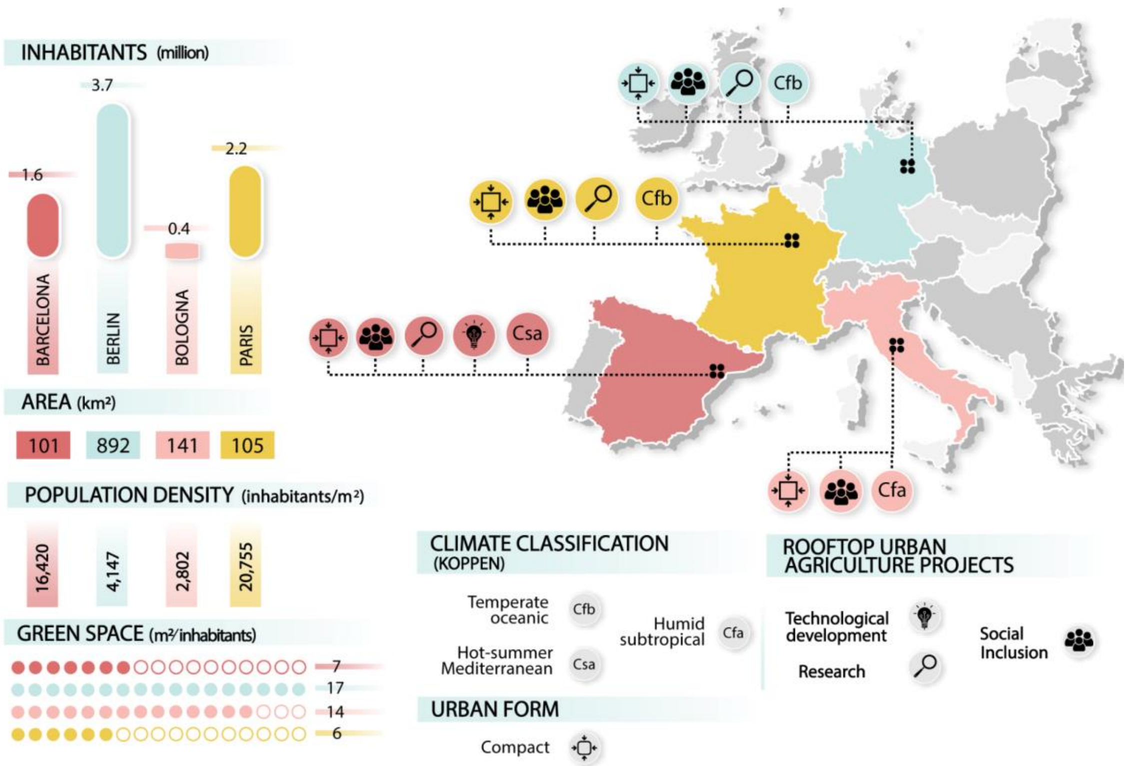

Figure 2.10. Summary of the main characteristics of the case studies.

Part II

Laboratory scale. Roof spectral characterization

Chapter 3

Laboratory-based spectral data acquisition of roof materials

CHAPTER 3 - Laboratory-based spectral data acquisition of roof materials

This chapter is based on the following journal paper:

Zambrano-Prado, P., Josa, A., Rieradevall, J., Pérez-Aragüés, F., Marchan, J. F., Gassó-Domingo, S., & Gabarrell, X. (2020). Laboratory-based spectral data acquisition of roof materials. *International Journal of Remote Sensing*, *41*(23), 9180-9205
https://doi.org/10.1080/01431161.2020.1798548

Abstract

Roof characteristics such as material type and their properties information are essential to integrating urban agriculture (UA), rainwater harvesting systems (RWHS), and energy systems on roofs. Roof materials can be identified from their spectral signatures. However, this identification requires a priori knowledge of the materials' spectral characteristics. The main perspective of this work is the future use of spectral data for roof classification. A common practice in mapping materials is the use of spectral libraries. In this regard, this work describes a novel framework for laboratory-based spectral data acquisition. The reflectance data of common, recently introduced (plastics and metals), and representative roof materials from the Mediterranean region were obtained. Data acquisition was conducted in a laboratory under controlled conditions using a high-spatial-resolution (HSR) sensor, which is usually used for airborne surveys. Large variations in the spectral reflectance data were observed due to the composition of the roof material. Flat spectral signatures were found for fibre cement, concrete, gravels, and some metals, especially from the near-infrared (NIR) spectral region. Colour and surface finish greatly influence the visible (VIS) spectral range. It was confirmed that the view angle did not modify the spectral shapes. A collection of 39 spectral data of roof materials (ceramics, concrete, fibre cement, metals, plastics, paints, stone, and wood) were compiled into a spectral library that is available online.

Part III

Building and urban scale. Mapping roofs for food, water, and energy production in a Mediterranean region

Chapter 4

Mapping roof materials in cities for food, water, and energy production: A Mediterranean metropolitan area case study

CHAPTER 4 - Mapping roof materials in cities for food, water, and energy production: A Mediterranean metropolitan area case study

From this chapter, a paper has been extracted and submitted in a peer-review indexed journal with the following co-authors: Perla Zambrano-Prado, Alejandro Josa, Joan Rieradevall, Ramon, Alamús, Fernando Pérez, Juan Marchan, Santiago Gassó, Xavier Gabarrell

Abstract

In recent years, rooftops have been used as productive spaces for local resource (e.g., food, water, or energy) production. The main objective of this study is to demonstrate the potential of hyperspectral data to identify roof materials in cities. The case study is The Vallès Occidental region, located north of Barcelona. The total area of interest spans 15 km^2. To obtain hyperspectral image from the case study, two hyperspectral airborne sensors were simultaneously operated: Airborne Imaging System for Different Applications (AISA) Eagle II and the Thermal Airborne Spectrographic Imager 600 (TASI-600). Seven roof classes were identified using k-means clustering algorithm. Most of the roofs were identified as metals (33%), followed by ceramic tiles (22%). To validate the classification procedures, an accuracy assessment was developed using an error matrix. The study demonstrates that hyperspectral imagery data are a powerful tool to classify roof materials without prior information in urban environments. Although hyperspectral data provided detailed spectral information on the scene, there are still misclassifications among some classes which must be addressed in future works. Results showed great potential for food production (51% of roofs) and for rainwater harvesting and solar energy systems (84% of roofs). Nevertheless, these assumptions are based on considering only the roof materials for a more reliable assessment of this potential, more criteria are needed such as urban planning, economic feasibility, building characteristics and technical requirements.

Keywords

Sustainable cities; urban agriculture; rainwater; solar energy; remote sensing

4.1 Introduction

4.1.1 Remote sensing and hyperspectral imagers

Hyperspectral imagers also known as spectrometer imagers (Goetz, 1985), is a relatively new field in remote sensing (e.g., satellite and airborne sensors) and have been rapidly grown during the last three decades. Hyperspectral remote sensing (HRS) captures spectral information composed of many contiguous spectral channels (e.g., 30 to about 200 at 10-20 nm interval) of each pixel in a cube-like image (Shippert, 2004). In contrast most of the multispectral imagers capture spectral information at a few (typically from 4 to 10) wide spectral channels, separated by spectral segments (100–200 nm interval) where no measurements are taken (Gupta, 2018; Shippert, 2004). Hyperspectral imagery provides high spectral and spatial resolution, therefore, a detailed pixel spectrum with much more information about surfaces than the available in multispectral imagery pixel spectrum (Heiden et al., 2012).

Urban areas constitute a complex mosaic of materials, in this sense, many studies; using hyperspectral imagery to classify urban surfaces have been carried out. Hyperspectral imagery, provide data to discriminate between spectrally similar materials, usually present in urban environments (Heiden et al., 2007; Priem & Canters, 2016; T. Wang et al., 2016).

4.1.2 Identification of urban surface materials

Heiden, Roessner, Segl, & Kaufmann (2001) identified 79 spectral classes of urban surfaces from Dresden, Germany. These classes were obtained using both spectral signatures (field spectral measurements) and hyperspectral imagery, acquired from a HyMap airborne sensor. A variability within group materials (mineral/ceramic, synthetic - polyethylene, and metals) due to differences in brightness and age of roofs was found.

Heiden et al. (2012) used hyperspectral imagery, acquired from a HyMap airborne sensor to map materials of Munich, Germany. Tiles, bitumen, metal, concrete, and plastic roof materials were found. Results also showed, that roofing materials, can be automatically detected with a high reliability, even where the material type was unknown, due to their distinct spectral reflectance characteristics. However, a large number of mixed pixels (around 50%; mix of materials in same pixels) was also detected within the study area. In addition, some limitations in mapping materials (of small urban objects) due to the spatial resolution (4 m pixel size) of the HyMap airborne sensor were found.

Priem and Canters (2016) used hyperspectral imagery data (252 spectral bands and 2 m spatial resolution) for mapping materials from the city of Brussels (Belgium). An identification of materials, including roof materials (ceramic tiles, fiber cement, and shingle) was done. Results showed some confusions to identify materials, due to spectral heterogeneity and similarity. The most significant confusion was detected between bright roof material, concrete and, to some extent, bare soil and between dark shingle, bitumen and hydrocarbon roofing.

As the literature indicate, mapping materials in urban areas remains a challenge. Some reasons are the diversity and spectral ambiguity of some materials, the complex geometry, and the presence of shadows (M. Herold et al., 2003; Moreira & Galvão, 2010).

The task of classifying data, derived from hyperspectral imagers, is essential for diverse studies in cities. Different machine learning approaches exist for classifying remotely sensed data. These approaches can be categorized as supervised and unsupervised (Olaode et al., 2014).

Supervised classification have been well explored in many works (L. Zhang et al., 2019) and is based on using samples of known classes (training samples) to classify pixels of unknown identity. In this technique algorithms search for pixels with similar characteristics to those in the input training sample, which are usually collected from fieldwork or remote sensing image data (Congalton, 1991; Kotsiantis et al., 2006). Unsupervised classification works with algorithms that infer patterns without any training samples (Olaode et al., 2014).

However, only a few studies have focused on the classification of roof materials using hyperspectral imagery data (Herold et al., 2003), and most approaches have focused on asbestos-containing materials (Książek, 2015; Osińska-Skotak & Ostrowski, 2015; Tommasini et al., 2019).

The main perspective of this work is mapping roof materials for assessing the roof suitability for food, water, or energy (FWE) production systems since rooftops can be used for food production (e.g., through the installation of rooftop greenhouses or open-air agriculture), water collection (e.g., rainwater harvesting systems) or energy systems (e.g., solar photovoltaic or solar thermal panels) (Toboso-Chavero et al., 2018) to the aim of create more sustainable cities, through the local production of food, water and energy resources.

In recent years, the use of rooftops in cities to integrate FWE systems started to emerge. The Fertilecity® project (Fertilecity, 2018) is an example of water collection and food production system on buildings. However, to assess the viability of and potential of FWE production systems, roof characteristics such as slope, solar radiation, roof material, effective area, and shade are required. Roof materials are related to a building's load-bearing capacity, which is essential for supporting the weight of FWE infrastructures. Furthermore, in the case of water collection, roof materials are related to runoff coefficient and water quality (Farreny et al., 2011; Nadal et al., 2017; Sanyé-Mengual et al., 2015a).

The main objective of this study is to demonstrate the potential of hyperspectral data to identify roof materials in cities. In this regard, the particular objectives are 1) to map roof class materials for a Mediterranean urban region, 2) to validate the roof classification and 3) to quantify the feasibility of using the rooftop for FWE production in a Mediterranean urban region considering roof material classes.

4.2 Methods

4.2.1 Study area

The Metropolitan Area of Barcelona, Spain, represents one of the largest metropolitan areas in Europe. The MAB comprises 636 km^2 area, 36 municipalities and a population of 3,239,337 people. Almost half (48%) of the territory is urbanized (Àrea metropolitana de Barcelona, 2019). The study area is located in El Vallès Occidental, a county in the providence of Barcelona located north of the city of Barcelona. The study area comprises five municipalities, three of which are part of the MAB (Badia del Vallès, Barberà del Vallès and Cerdanyola del Vallès) and two wich are not (Sabadell and Santa Perpètua de la Mogoda). The total area of the study area is approximately 15 km^2. Table 4.1 describes the study area in terms of the municipalities and their populations and areas. The *area in the study* refers to the portion of the municipality that was considered for this study.

Table 4.1. Study area municipalities' information area, population, density, and area for this study.

Municipality	Total area km²	Population	Population density inhabitants/km²	Area in the study (%)
Badia del Vallès	0.93	13,417	14,427	100
Barberà del Vallès	8.31	32,839	3,952	90
Cerdanyola del Vallès	30.56	57,740	1,889	5
Sabadell	37.79	211,734	5,603	10
Santa Perpètua de la Mogoda	15.83	25,705	1,624	4

The study area is characterized by diverse population densities, building typologies (e.g., block social housing, detached and terraced houses), and building uses (e.g., industrial, residential, retail, office and public service buildings). Due to this diversity, we assume that a variety of roofing materials can be found in this area. The location and boundaries of the study area are shown in Table 4.1.

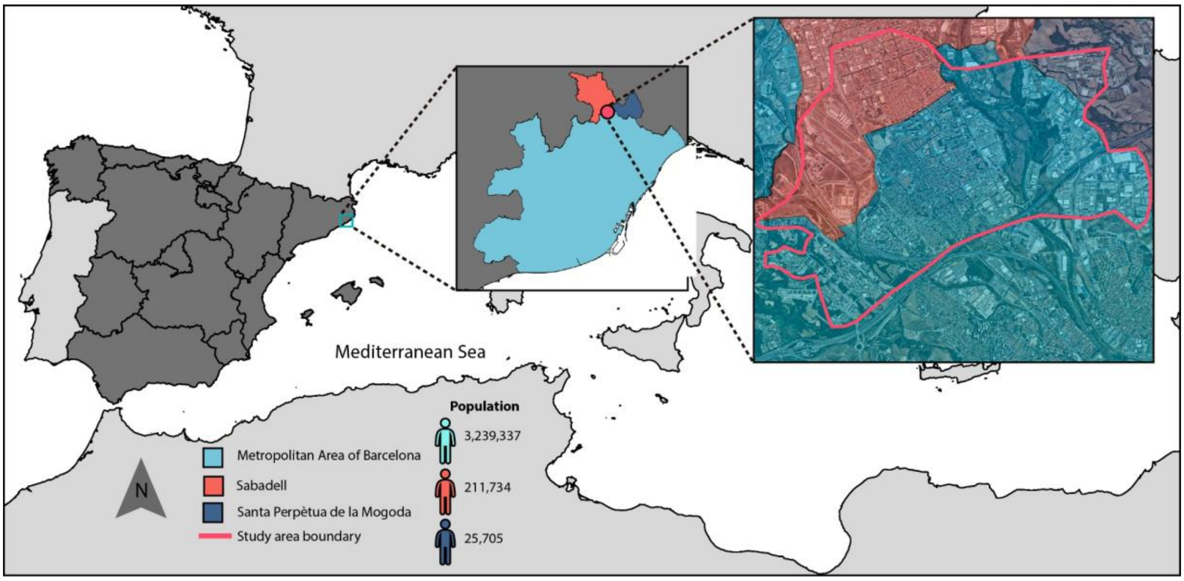

Figure 4.1. Location of the study area of El Vallès Occidental, Barcelona.

4.2.2 Equipment and materials

Data acquisition

The hyperspectral data of the study area were acquired on March 6, 2018 at 11:35 AM local time. The flight was conducted by the Institut Cartogràfic i Geològic de Catalunya (ICGC). Two hyperspectral airborne sensors were simultaneously operated: Airborne Imaging System for Different Applications (AISA) Eagle II and the Thermal Airborne Spectrographic Imager 600 (TASI-600).

AISA Eagle II, manufactured by Specim, is a hyperspectral visible and near-infrared (VNIR) pushbroom imager with a reflection grating and a two-dimensional charge-coupled device (CCD) solid-state array detector. The instrument operates by looking down in a fixed direction and imaging successive lines of the flown scene, building up a two-dimensional image as the platform moves forward. One dimension of the CCD covers the across-track spatial direction, while the other dimension accounts for the spectral domain.

TASI-600, manufactured by Innovation, Technology, Research, Excellence, and Science (ITRES), is a hyperspectral long-wavelength infrared (LWIR) pushbroom imager with a dispersing prism and two-dimensional mercury-cadmium-telluride detector. The sensor has a long-infrared array detector. The instrument operates by looking down in a fixed direction and imaging successive lines of the flown scene, building up a two-dimensional image as the platform moves forward. One dimension of the detector covers the across-track spatial direction, while the other dimension accounts for the spectral domain. Table 4.2 summarizes the flight parameters and technical characteristics of hyperspectral sensors.

Table 4.2. Flight parameters and technical characteristics of the hyperspectral imagers.

Parameter	AISA Eagle II	TASI-600
Field-Of-View (FOV)	38°	40°
Flight altitude	1650 m	
Spectral bands	252	32
Spectral range	400-900 nm	8,000-11,500 nm
Spectral resolution	2.5 nm	110 nm
Across-track Spatial pixels	1024 pixels	600 pixels
Pixel resolution width	1,1 m	2 m
Pixel resolution length	1,1 m	2 m
Swath width	1,126 m	1,200 m

Ancillary data

The flight described in Section 4.2.2.1 was specifically designed for this work. In addition to this flight ancillary data were required for the preprocessing and processing phases. A digital surface model (DSM) was provided by the ICGC. The DSM was built from a cloud of points obtained with a light detection and ranging (LiDAR) airborne sensor. The LiDAR flight was conducted in 2013, Table 4.3 describes the flight parameters and technical characteristics of LiDAR sensor. The point density was 4 points/m^2. The part of the point cloud classified as buildings was used to obtain a 3D model of buildings and to extract the roofs. The building footprints were extracted from the ICGC topographic database at a 1:5,000 scale.

Table 4.3 Flight parameters and technical characteristics of LiDAR airborne sensor.

Parameter	Leica ALS50-II
Field-Of-View (FOV °)	40
Flight altitude (m)	1,490
Pulse frequency (Hz)	134400
Sweep frequency (Hz)	35
Flight speed (knots)	100-120

Data procedure

In this section, data process workflow is presented. A detailed description of each stage is presented in the following sections. The pre-processing and classification procedures were performed with Environment for Visualizing Images (ENVI) and a QGis. After classification and accuracy assessment, a quantitative estimation of roofs in the study area with the potential to produce FWE was made. Figure 4.2 shows he main workflow of the process. The mina five stage are as follow: The preprocessing stage (section 4.2.2.4) was carried out in three steps: radiometric correction, geometric correction, and atmospheric correction.

1) The pre-processing stage (section 4.2.2.4) was carried out in three steps: radiometric correction, geometric correction, and atmospheric correction.

2) In the roof classification process (section 4.2.2.5), pixel mask was created, and dimension reduction was carried out. Subsequently, unsupervised classification techniques were performed.

3) A roof polygon class assignment (section 4.2.2.6) was made using the roof class map (raster), the building footprints and the abundance of pixels of each class in roof polygons.

4) In the accuracy assessment stage (section 4.2.2.7), a random selection of roofs (237) was verified to validate the classification procedures.

5) The analysis of the quantitative feasibility of using rooftops for FWE production (section 4.2.2.8) was carried out considering the roof polygon surface, the roof material classification results and literature.

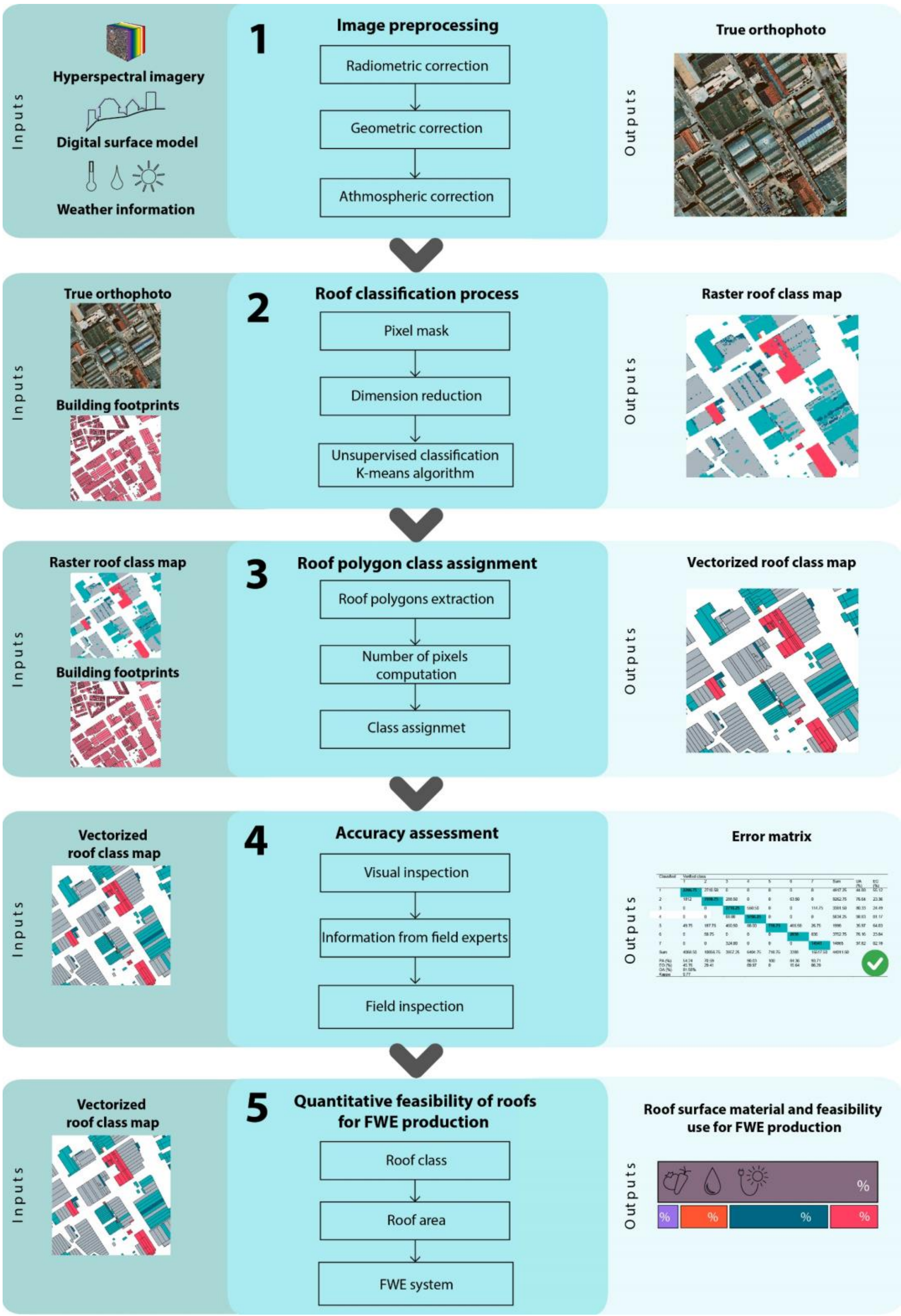

Figure 4.2. Diagram of the general workflow of the five main stages carried out: preprocessing, roof classification, roof polygon class assignment, accuracy assessment and the quantitative feasibility of using the rooftop for FWE production.

Preprocessing

The goal of preprocessing raw images is to derive a mosaic of orthoimages. This mosaic is a data cube with reflectance (VNIR spectrum) and emissivity (LWIR spectrum) values for each pixel in the image captured by HRS. This process was carried out in three steps:

Radiometric correction. Sensors record the intensity of the electromagnetic radiation that reaches each pixel as digital numbers (DNs). DNs were converted into spectral radiance, measured in W cm^{-2} sr^{-1} nm^{-1} by means of the manufacturer's radiometric calibration, which is performed yearly. This process is similar for both the VNIR and LWIR hyperspectral data.

Geometric correction .To georeferenced the images to real-world locations and to generate orthoimages, a geometric correction is necessary (Aspinall et al., 2002). HRS collects data pixel-by-pixel as the sensors scan across a track perpendicular to the flight line; for this reason, the ground location of pixels can jump dramatically from pixel to pixel due to several factors, such as the yaw and roll of the aircraft. Trajectory flight information and a DSM were used to project each pixel onto the ground. Simultaneously, with the hyperspectral image, HRS orientation data were recorded by an orientation system: global navigation satellite system (GNSS) and inertial measurement unit (IMU) data. Applanix system that integrates GNSS is pioneered in the use of direct georeferencing for airborne mapping and was used to obtain the orientation and the trajectory flight data (time, position and altitude for each line in the image). Trajectory flight was computed using the PosPacMM8 software developed by Applanix. True orthophoto was performed using a software developed for internal use by the ICGC since the HRS (AISA Eagle II and TASI-600) manufacturers (Specim and ITRES respectively) software's did not allow true orthophoto generation with occlusion detection. As the work is focused on rooftops, a true orthophoto was required. In this way, the rooftops were properly georeferenced. The LiDAR-derived DSM together with the trajectory were used to geometrically correct and mosaic the images.

Atmospheric correction. In this step, atmospheric compensation was carried out. On the one hand, radiance (VNIR) data was converted into reflectivity data. On the other hand, a temperature/emissivity separation (TES) technique tailored to the spectral properties of TASI (Pipia et al., 2010) was used for the LWIR data. Temperature, National Centers for Environmental Prediction (NCEP) humidity and pressure vertical profiles (Barsi et al., 2003) were retrieved for the flight. To link the NCEP profiles to the actual atmosphere on the ground, the weather information provided (every 30 minutes) by the Cerdanyola del Vallès Automatic Weather Stations Network (XEMA) station (*Servei Meteorològic de Catalunya, Automatic Weather Stations (XEMA)*, 2018), located close to the study area, was used. Then, moderate resolution atmospheric transmission (ModTran5.0) simulations (Aspinall et al., 2002) were used to generate atmosphere transmissivity lookup tables (LUTs). A 2D interpolation was carried out to calculate the attenuation parameter for each pixel at each band wavelength (VNIR data) and to apply the TES technique to the LWIR data. Finally, a true orthophoto with reflectance and emissivity data was obtained and used as input in the classification process.

Roof classification process

As the study is focused on roofs, nonbuilding pixels (e.g., streets, sidewalks, and parks) were masked out from the true orthophoto in the analysis. For this process, building footprints extracted from the ICGC 1:5,000 topographic database were used. After masking the pixels, dimension reduction was performed. This procedure addresses the importance of handling hyperspectral data more efficiently to address dimensionality issues that have a detrimental effect on the computational processing (Gao et al., 2013; Green et al., 1988). Once dimension reduction was carried out, unsupervised classification approaches were performed, since there was no knowledge about the typology and abundance of each class of roofs in the study area.

Dimension reduction. Due to the nature of hyperspectral sensors, the image data cube has 252 bands in the VNIR spectrum and 32 bands in the LWIR spectrum. For this work, a maximum noise fraction (MNF) method was applied (Gao et al., 2013; Green et al., 1988). To project the data in a lower-dimensional subspace, the channels with the highest variance were selected. VNIR spectrum was reduced to 16 bands and the LWIR spectrum was reduced to 9 bands to retain the significant features of each part of the spectrum.

Unsupervised classification. There are different approaches and classifiers in machine learning for classifying remotely sensed data. Common classifiers such as maximum likelihood, artificial neural network or spectral angle mapper (Helmi Zulhaidi Mohd Shafri et al., 2007) have been used for land cover classification. However, data set and prior field knowledge is necessary for training samples (Momeni et al., 2016). Since the area of interest covers more than one municipality with heterogeneity of building types and uses (educational, services, housing, industrial, commercial), was assumed that there were different types of roof materials. However, there was no prior knowledge about the typology and abundance of each class of roofs in the study area for use as training samples. The only previous information available was orthophotos outdated compared to flight. For these reasons, a cluster analysis method of unsupervised classification (k-means clustering algorithm) was used for this work, as an alternative to other classifiers, that have been more robust when reliable training data is available. After the data were clustered by the algorithm, the cluster classes were labeled by visual inspection.

Roof polygon class assignment

The classified raster image was vectorized it was used the roof polygons extracted from the building footprints using the LiDAR DSM roof planes. For each roof polygon (roof plane), the histogram of the classes (number of pixels) in the polygon was computed. The majority class was set as the roof polygon class.

Accuracy assessment

Possible errors during spectral classification were assessed. The validation process was carried out through three different approaches (see below) and using a stratified sample. The number of validation roofs was estimated to ensure a proper representation of each class. In this sense, at least 25 roofs were randomly selected for each class. Roofs were selected from across the entire study area. However, verified information and access to the roofs were the determinants for the selection. For this purpose, about half (61.96%) of these verification roofs were taken from the Universitat Autònoma de Barcelona (UAB) area, located in the Cerdanyola del Vallès municipality. Data verification was performed in three different ways:

1) Visual inspection: an exhaustive visual inspection was made from an aerial photograph by referring to Google Earth imagery and Google Street View.

2) Information from field experts: meetings were held with architects from the infrastructure and maintenance unit of the UAB to confirm the roof materials.

3) Field inspection, together with verified information: some of the randomly selected roofs from the UAB area were visited.

After roof verification, a quantitative accuracy assessment of the unsupervised classification results was conducted. The objective of a classification accuracy assessment is to provide an indication of how closely a classified image matches the ground truth information (e.g., reference data or imagery). By randomly selecting a certain number of samples and evaluating the correctness of each sample against the reference, statistics are calculated to validate the output of the classification (Carletta, 1996; Congalton, 1991). The accuracy assessments were based on the error matrix method (Congalton, 1991): an error matrix is used to describe the performance of a classification model on a set of test data for which the true values are known. The overall accuracy (OA) is the portion of pixels (pixels contained in polygons or study areas) that were mapped correctly. The OA is calculated by summing the number of correctly classified pixels and dividing it by the total number of reference pixels. Another commonly used accuracy indicator is the Kappa (K) coefficient (Congalton, 1991). It is a measure of the overall statistical agreement between the classification result and the true values in an error matrix (Lu & Weng, 2007; H. Zhang et al., 2018). A K coefficient of 1 represents perfect agreement, while a value of 0 represents no agreement. The K coefficient has the advantage of statistically comparing two different classification procedures. In addition to the OA, the accuracy of each class identification needs to be assessed. Errors were also calculated. There are two kinds of errors: errors of omission (EO) occur when pixels are omitted from the correct class and are included in a different class; errors of commission (EC) occur when a pixel is incorrectly included in a certain class. The user's accuracy (UAc) and producer's accuracy (PA) metrics were also calculated. The UA (or reliability) is the probability that a pixel is predicted to be in a certain class that represents that particular class on the ground. The UA is a complement of the EC. The probability is based on the fraction of correctly predicted values over the total number of values predicted to be in a class. The PA is the probability that a value in each class was classified correctly. The PA is a complement of the EO.

Quantitative feasibility of rooftop for FWE production

Once the roof materials have been identified, this information was used to analyze their potential for FWE production systems. The analysis was carried out considering the roof polygon surface, the roof material classification results and the literature related to suitable roof materials for FWE production systems. The works *assessing rooftop greenhouse potential of non-residential areas using airborne sensors* and the *guide for assessing the Implementation of the roof mosaic* developed by Nadal et al. (2017) and Toboso-Chavero et al. (2018) respectively, and the work *roof selection for rainwater harvesting: Quantity and quality assessments in Spain* (Farreny et al., 2011) were used as a reference to calculate quantitative feasibility of rooftops for FWE production. These works, establish divers criteria (e.g., urban, agricultural, building, technical) to integrate FWE systems, these methodologies also include the criteria for analysis and quantification of the potential area to integrate these systems (Nadal et al., 2017; Toboso-Chavero et al., 2018), and environmental assessment (Toboso-Chavero et al., 2018). Figure 4.3 illustrates the definition of suitable roof material for each type of system (food production, rainwater collection and energy production), these parameters, as well as the parameters to calculate the roof potential for integrating these systems were taken from the three works described above.

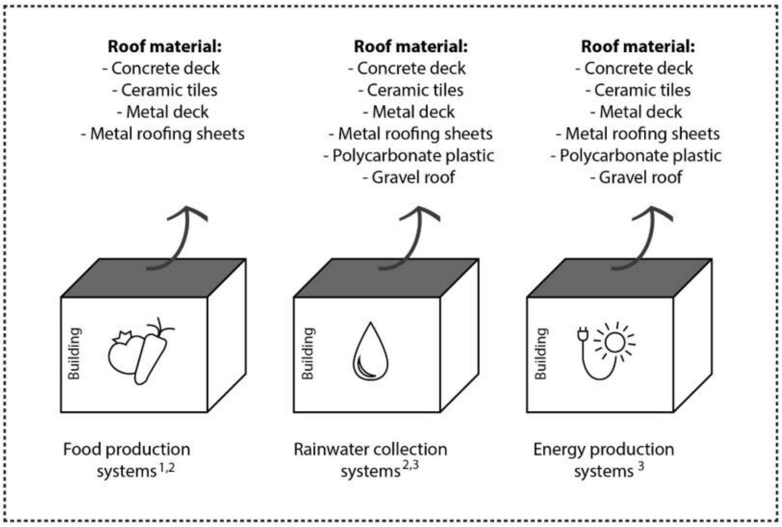

Figure 4.3. Roof material considered for the quantitative feasibility of rooftop to integrate FWE systems. [1]Nadal et al. (2017); [2] Toboso-Chavero et al. (2018); [3] Farreny et al. (2011).

To calculate the roof feasibility, first the total surface of each roof class in the study area was calculated, a sum of roof polygon surfaces belonging to each class was made. The results were related to the suitable roof materials for integrate each system to quantify the feasibility of using the rooftop for FWE production.

4.3 Results

4.3.1 Roof classification

An image with a spatial resolution of 1 m was obtained. The total area of classified roofs was 3.07 km^2 and comprising 42,386 roof polygons ranging from 0.25 m^2 to 13,480.5 m^2. Figure 4.4 illustrates the distribution of roofs in the study area by Municipality. According to their surfaces calculated based on 2D measurements (since in the orthophoto the roofs are 2D), roofs were divided by ranges ≤25 m^2; ≥25 m^2 and ≤100 m^2; ≥100 m^2 and ≤300 m^2; ≥300 m^2 and ≤1000 m^2; and ≥1000 m^2. Barberà del Vallès was the municipality with the highest roof area (1.70 km^2), followed by Sabadell (0.86 km^2), Cerdanyola del Vallès (0.23 km^2), Badia del Vallès (0.10 km^2), and Santa Perpètua de la Mogoda (0.18 km^2).

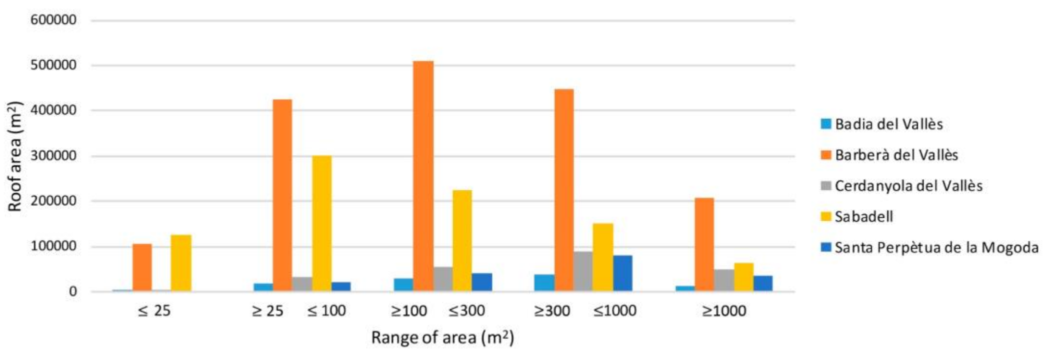

Figure 4.4. Distribution of roofs by area and Municipality.

Figure 4.5 illustrates unsupervised roof classification results. It was identified seven roof classes: 1) white finished roofs, which are usually composed of membrane roofing or waterproof paints. Membrane roofing systems are most commonly made from synthetic rubber, thermoplastics such as polyvinyl chloride (PVC), or modified bitumen made from asphalt and a variety of rubber, 2) metal roof class was found into white, gray, green and blue colors, and into sheet structure or metal sandwich panel format, 3) red finished roofs were found and identified as red ceramic tile roofs, 4) metals (metal sheets or metal sandwich panels) and membrane roofing in red. Normally, finished membrane roofs are composed of concrete or roof deck systems, 5) green roofs (i.e., roofs where a vegetation system was installed), 6) fiber cement roofs and 7) roofs with gravel and dark membrane roofing. Usually, gravel finish roofs are composed of a sturdy concrete structure.

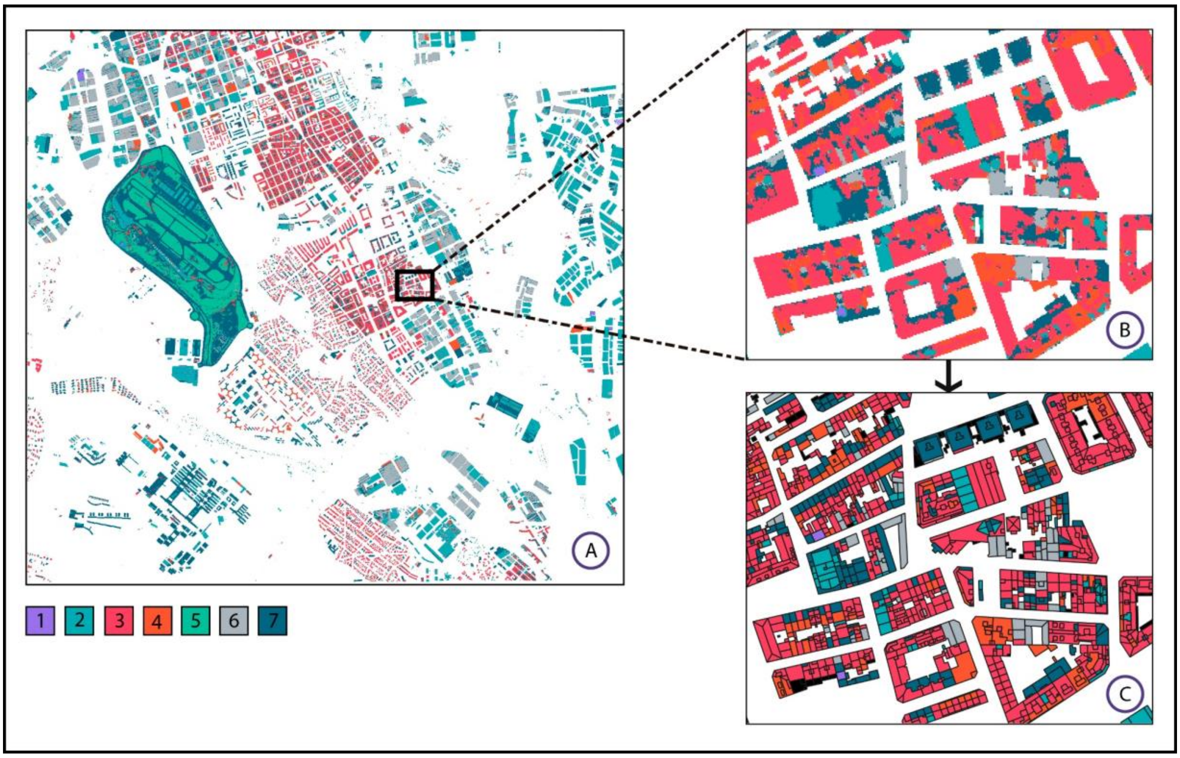

Figure 4.5. Unsupervised roof classification results of the complete study area (A); detail of the unsupervised roof classification from residential buildings in Barberà del Vallès (B); detail of the unsupervised roof classification using roof vectorization and majority class assignment (C). Each color represents one roof class. Numbers in the image identifies the color that corresponds to a class: (1) membrane roofing/waterproof paint (white); (2) metals (white, gray, blue and green); (3) ceramic tiles (red); (4) metal/membrane roofing (red); (5) green roofs; (6) fiber cement and (7) gravel/membrane roofing (gray and black).

4.3.2 Accuracy assessment

In total, 237 roof polygons were randomly selected for verification. These roof polygons correspond to a total roof area of 44, 011 m^2. Table 4.4 shows the distribution of the roof polygons in the study area and the surface used in the validation process. An average of 34 roofs were selected for each class (seven), ranged from 25 m^2 to 1,812 m^2. The distribution of the verification was as follow: visual inspection (49% of the roofs), information from field experts (22% of the roofs), field inspection, together with verified information (28% of the roofs). An error matrix for the unsupervised classification is summarized in Table 4.5.

Table 4.4. Distribution of roofs in the study area for validation process. Numbers are the roof classes: (1) membrane roofing/waterproof paint (white); (2) metals (white, gray, blue and green); (3) ceramic tiles (red); (4) metal/membrane roofing (red); (5) green roofs; (6) fiber cement and (7) gravel/membrane roofing (gray and black). R represents the number of verified roof polygons. Roof area (A) is expressed in m^2.

	Class															
Municipality	**1**		**2**		**3**		**4**		**5**		**6**		**7**		**Sum R**	**Sum A**
	R	**A**	**R**	**A**	**R**	**A**	**R**	**A**	**R**	**A**	**R**	**A**	**R**	**A**		
Badia del Vallès	2	316	2	1997	2	70	3	168	6	362	2	204	2	511	19	3628
Barberà del Vallès	12	1466	2	1803	2	743	5	482	9	628	2	139	2	1096	34	6357
Cerdanyola del Vallès	4	752	30	5170	30	4762	12	1924	2	60	21	2803	31	12804	130	28275
Sabadell	9	1332	2	137	2	68	17	737	8	949	2	73	2	158	42	3454
Santa Perpètua de la Mogoda	3	1052	2	156	2	191	1	72	0	0	2	145	2	686	12	2302
Sum	30	4918	38	9263	38	5834	38	3383	25	1999	29	3364	39	15255	237	44016

Note: The UAB campus is located at Cerdanyola del Vallès Municipality

Table 4.5. Error matrix for the unsupervised classification results by number of roofs polygons. The seven roof classes are: (1) membrane roofing/waterproof paint (white); (2) metals (white, gray, blue and green); (3) ceramic tiles (red); (4) metal/membrane roofing (red); (5) green roofs; (6) fiber cement and (7) gravel/membrane roofing (gray and black). Range of area (RA) of verified polygons (≥25 - ≤100; ≥100 - ≤300; ≥300 - ≤1000; ≥1000) expressed in m^2.

Classified	Verified Class										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**Sum**	**UA (%)**	**EC (%)**	**RA-UA (%)**
1	**17**	13						30	57	43	-
≥25 - ≤100	9	4						13		31	53
≥100 - ≤300	6	6						12		50	35
≥300 - ≤1000	2	3						5		60	12
2	1	**35**	1			1		38	92	8	-
≥25 - ≤100		15				1		16		6	43
≥100 - ≤300		14	1					15		7	40
≥300 - ≤1000		5						5		0	14
≥1000	1	1						2		50	3
3			**29**	6			3	38	76	24	-
≥25 - ≤100			23	4			3	30		23	79
≥100 - ≤300			5	2				7		29	17
≥300 - ≤1000			1					1		0	3
4			2	**36**				38	95	5	-
≥25 - ≤100			2	19				21		10	53
≥100 - ≤300				15				15		0	42
≥300 - ≤1000				1				1		0	3
≥1000				1				1		0	3

5	1	3	7	1	**4**	8	1	25	16	84	-
≥25 - ≤100	1	2	6	1	2	8	1	21		90	50
≥100 - ≤300		1	1		1			3		67	25
≥300 - ≤1000					1			1		0	25
6		2				**22**	5	29	76	24	-
≥25 and ≤100		2				12	4	18		33	55
≥100 and ≤300						10	1	11		9	45
7			4				**35**	39	90	10	-
≥25 - ≤100			3				10	13		23	29
≥100 - ≤300			1				5	6		17	14
≥300 - ≤1000							17	17		0	49
≥1000							3	3	100	0	9
Sum	19	53	43	43	4	31	44	**237**			
PA (%)	89	66	67	84	100	71	80				
EO (%)	11	34	33	16	0	29	20				
OA (%)	75.34										
Kappa	0.7										

Note: RA-UA is the proportion of the probability that a roof polygon, according to the area range, was predicted to be in a certain class that actually represents that particular class.

The error matrix shows all possible correlations between the verified class and the predicted class. The diagonal elements (boldface) represent the areas that were correctly classified. The OA and the K coefficient for the unsupervised results were 75% and 0.7, respectively (Table 4.5). Regarding the accuracy of specific classes, cells (except boldface) contain classification errors.

The green roof (class 5) achieved the highest PA (100%) while the UA was very low 16%. This result means, that 100% of this class roofs polygons were correctly identified as green roof and 16% of the roofs classified as “green roof” were actually “green roof”; 84% (EC) were omitted from the correct class and are included in a different class. The second class with the highest PA (89%) was the membrane/waterproof paint (white) roofing class while the UA was lower

57%. This result means, that 89% of this class roofs polygons were correctly identified as membrane/waterproof paint (white) and 57% of the roofs classified as "membrane/waterproof paint (white)" were actually "membrane/waterproof paint (white)"; 11% were mistakenly classified (EO) into the metal (white, gray, blue and green) and green roofs classes. The third class with the highest accuracy values (PA 84% and UA 95%) was metal/membrane (red); 16% were mistakenly classified (EO) into the ceramic tiles and green roofs classes. The gravel/membrane roofing (gray and black) obtained 80% of PA and 76% of UA, this class was mistakenly classified (EO 20%) into metals (class 2) and green roofs (class 5). In contrast, the metals (white, gray, blue and green) class achieved the lowest values. The PA was 66%, while the UA was 92%; the EO percentage was 34% and the EC percentage was 8%. Followed by metals (class 2), the ceramic class achieved the lowest PA (67%), while the UA (76%) was higher, this class, was mistakenly classified into metals (classes 1 and 4), green roofs (class 5), and gravel (class 7). The fiber cement class obtained 71% of PA and 90% of UA, 26% (EO) were mistakenly classified into gravel, green roof, and ceramic tiles classes.

4.3.3 Quantitative feasibility of rooftop for FWE production

Figure 4.6 shows the surface percentages of each roof class in the study area according to the classification results. Metal (white, gray, blue and green) roofs comprised the largest area (33%), followed by ceramic tile and gravel/membrane which were found in similar proportions (22% and 21%). The 16% of roofs were fiber cement. Red metal/membrane roofing was found in a low proportion (7%). Finally, white membrane/waterproof paint roofing and green roofs had the lowest surface representation (0.9% and 0.1%). Considering the classification results, approximately 51% of roofs (white membrane/waterproof paint roofing, gravel/membrane roofing, ceramic and red metal/membrane roofing) could be used for FWE production. Thirty-three percent of roofs in the study area (metal roofs) could be used for the implementation of rainwater harvesting or solar energy (solar photovoltaic or solar thermal panels) systems. Sixteen percent of roofs (fiber cement) could not be considered productive rooftops because of their insufficient load-bearing capacity.

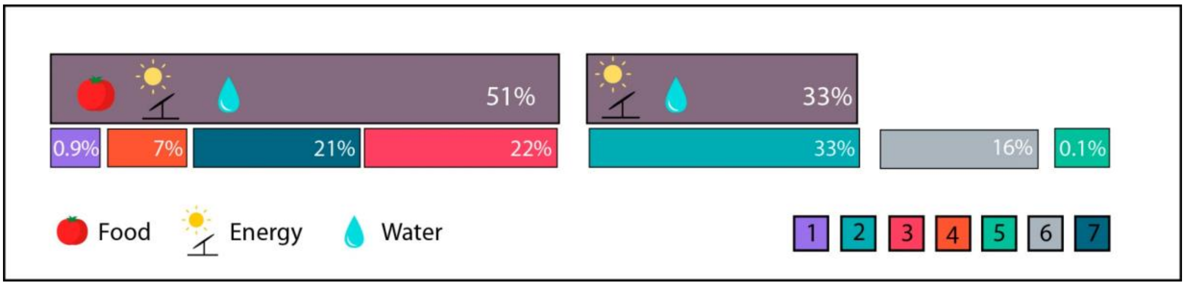

Figure 4.6. Surface percentages of each roof class in the study area according to the unsupervised results and percentages of potential rooftop uses to produce FWE. Each color of the small boxes in the lower right corner represents one roof class and is associated with the percentages of each roof class in the study area: (1) membrane roofing/waterproof paint (white); (2) metals (white, gray, blue and green); (3) ceramic tiles (red); (4) metal/membrane roofing (red); (5) green roofs; (6) fiber cement; and (7) gravel/membrane roofing (gray and black).

4.4 Discussion

The PA value of the metal (white, blue, gray and green) roof class for unsupervised classification (66%) was the lowest. Osińska-Skotak & Ostrowski (2015), obtained similar low PA, from 39.4 to 52.1%, for the metal class with pixel-oriented approach classification. The metal (white, blue, gray and green) roof class was quite often classified as white membrane roofing/waterproof paint. After a careful analysis, it was found that the 72% of EO corresponded to the "white membrane roofing/waterproof paint" class, and 100% of the confusion between metal and white membrane roofing/waterproof paint classes were because some of the white roofs were metal finished in white color. This finding can explain the low PA and UA values and demonstrate how the color finishing affects accuracy classification. In this sense, the use of LWIR spectrum brings information to identify these different classes (Kotthaus et al., 2014). However, SWIR spectrum range could bring better information to classify urban materials with highest accuracy values (Heiden et al., 2001b). Chen et al. (2018a) attained a similar PA value (82.46%) for the red roof class to that attained in this work for the red metal/membrane roofing class (PA 84%). The red metal/membrane roofing class was mainly confused with the red ceramic tile class since most of the ceramic tiles in the study area are red. However, in the case of the red ceramic tile class, the confusion is not obvious, since it was found a EO with almost all the classes except the membrane roofing/waterproof paint (white) and fiber cement roof ones. Osińska-Skotak and Ostrowski (2015) obtained higher results for asbestos cement roofing (PA 81–85%) to those obtained in this work for fiber cement (PA 71%), the low accuracy (PA), is related to trees (63% of 89% of EO) that were found over fiber cement roofs, these roofs were mistakenly classified into green roofs. The results obtained by Osińska-Skotak and Ostrowski (2015) for felt roofs (PA from 48.4 to 62.5%) are lower than those obtained in this work (PA 80%) for gravel/ membrane roofing (gray and black), which is a similar material.

As already mentioned, the main perspective in this work for mapping roof classes is centered on the interest in the future implementation of FWE systems on rooftops. For this reason, material type was the decisive element of division classes, according to different roof construction systems. However, discrimination between red metal and red membrane roofing was not possible to perform in this classification. For the implementation of FWE, color surface finishing is not a decisive element; nevertheless, spectral information obtained from VNIR spectral range provided color division. In this sense, LWIR provided spectral information to discriminate between red materials (ceramic and metal and membrane roofing); and white roofing (membrane roofing/waterproof paint and metal materials) a major consideration to assess the suitability of FWE systems.

After careful error analysis, unsupervised classification revealed that some roof polygons of the green roof (12, which represents 57% of EC), gray and black gravel/membrane (1, which represents 25% of EC) and metal (1, which represents 33% of EC) were not truly algorithm classification errors, given that the information in the scene captured by HRS was correct. Because some roofs had different, additional kinds of installations, such as metal air conditioners, the algorithm classified these roof pixels as "metal"; however, the roof material was not metal (i.e., ceramic tiles or gravel). In the case of green roofs, more than half (57%) were covered by trees, which means that the sensor actually captured the vegetation and metal over the roof. The algorithm classified these pixels as "green roof," but these roofs were not green, metal or gravel roofs. For this reason, some classes, such as green roofs, result in a low UA that affects the OA and the K coefficient. Figure 4.7 illustrates two different examples of these cases.

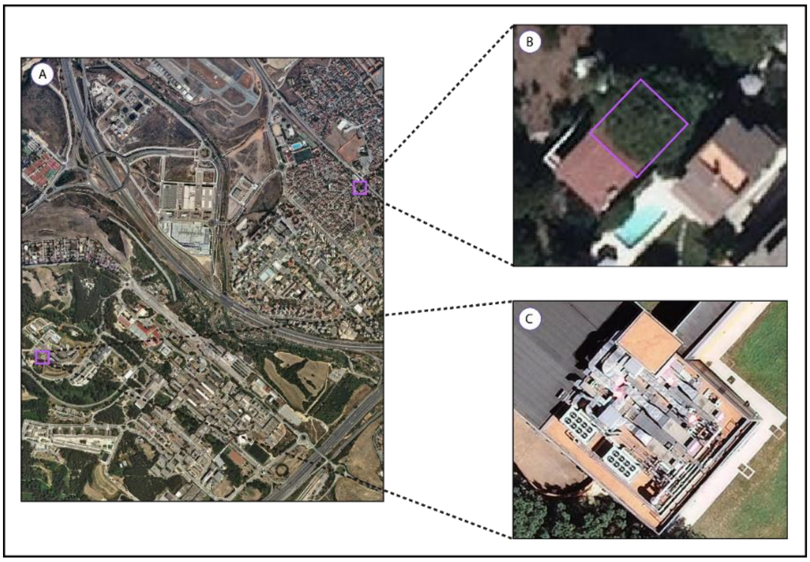

Figure 4.7. (A) Aerial image of the study area. (B) Roof of a detached house covered by a tree/ceramic tile roof that was classified as a green roof. (C) Roof from a veterinary hospital (UAB) covered with metallic installations/ceramic roof that was classified as a metal roof.

The Barcelona roofs with the potential to integrate food production systems (i.e., rooftop greenhouses) identified in this work are similar to those identified by Sanyé-Mengual et al. (2016) (51% vs. 53.2%-73.2%, respectively). Other studies (Nadal et al., 2017; Sanyé-Mengual, et al., 2015a) identified a lower potential for implementing rooftop greenhouses approximately 3% and 8%, respectively, for industrial areas in Barcelona. In the case of water, roofs with the potential to integrate RWHS identified in this work are similar to those identified by Campisano, D'Amico, and Modica (2017) in a Mediterranean Italian region (84% vs. 95%, respectively). The Barcelona roofs with the potential to integrate energy production systems (i.e., solar photovoltaic and thermal systems) identified in this work (84% of roofs) are higher than the roofs (65%) identified by Groppi, de Santoli, Cumo, and Astiaso Garcia (2018). However, the quantification in this work was based on considering only roof materials, which could result in higher values for potential rooftop for FWE production.

In general, flat roofs with a minimum load-bearing capacity of 200 kg/m^2 or 80-100 kg/m^2 are considered feasible for rooftop greenhouses and open-air agriculture systems, respectively. Concrete deck roof systems with a high load-bearing capacity (e.g., concrete deck roofs with concrete pavers or ceramic tiles) are ideal for these purposes. In the case of Spanish regulations, concrete deck roof systems must support a minimum load of 200 kg/m^2 (Nadal et al., 2017). In the case of implementing rainwater harvesting systems, roof material selection depends on the location of the water tank. However, if the water tank is not located over the roof, almost any roof material could be suitable for rainwater harvesting system. Nevertheless, some kind of roof material (e.g., asbestos roofing) can affect the quality of harvested rainwater (Farreny et al., 2011; J. Y. Lee et al., 2012; Olaoye & Olaniyan, 2012). Furthermore, roof materials cause different runoff behaviours. A high runoff coefficient depends on the roughness and the slope of the roof material. Sloped roofs with smooth materials (such as metals) may harvest 50% more rainwater than flat, rough roofs (Farreny et al., 2011). Roofs such as concrete deck roofs or metal panel sandwich roofs can be suitable for solar energy production, taking into consideration 12.5 kg/m^2 of load-bearing capacity for solar photovoltaic panel (framed module) or solar thermal panel installations (Best Practice Guide Photovoltaics (PV). Sustainable Energy Authority of Ireland, 2018).

4.5 Conclusions

This study demonstrates the great potential for using HRS to classify roof materials without prior information. To our knowledge, this is the first study to focus on the identification of roofs with the main perspective of being future applications of FWE production. Most of the previous studies have focused on the detection of asbestos, which is necessary for addressing health problems. Nevertheless, the new challenges faced by cities necessitate information regarding building roofs to integrate FWE systems into the roofs and produce local resources, to the aim of create sustainable cities. Only a few works have focused on roof materials, and most of them identified roofs based on color (i.e., red, blue, green, white roofs).

Membrane roofing/waterproof paint (PA 89%), red metal/membrane roofing (PA 84%) and gravel/membrane roofing (PA 80%) where the classes with the highest accuracy values. Although hyperspectral data provide detailed spectral information on the scene, there are still misclassifications among some classes. Metal (white, gray, blue and green) roofing and red ceramic tiles were the classes with the lowest PA (66% and 67%, respectively). Red ceramic tiles were mainly confused with green roofs (50% of the total EO), followed by gravel/membrane roofing and red metal (28.6% and 14%, respectively, of the total EO); however, 100% (metal), 43% (green roof) was not an algorithm error, due the existence of infrastructures or vegetation over de roof.

In future works, with a purpose of taking advantage of the roof as is the case in this work, it would be important to identify separate classes for metals and membrane roofing, due to the importance of the roof's load-bearing capacity by construction systems.

The verification process carried out in this work, using field inspections and interviews with field experts is important for obtaining reliable information when there is no previous knowledge of the study area.

Different kinds of elements on rooftops were found, such as the foliage of trees or different types of service items such as air conditioning units, pipes or other structures that can cause classification errors and decrease the accuracy. Assigning a class to roof polygons by pixel abundance is a good practice for certain data applications. However, this strategy can act as a barrier in the detection of roof materials, and accuracy values can be negatively affected. For future works, it is recommended to reconsider this strategy during the design of the classification process.

The 33% of roofs were identified as metals and 22% as ceramic tiles over the study area. The findings showed that 51% of roofs could be suitable for integrating crops and 84% for integrating RWHS and PV. However, these assumptions are based on considering only the roof materials. For a reliable assessment of this potential, more work and criteria are needed, such as urban planning (e.g., urban laws), economic feasibility, building characteristics (e.g., roofs without installations or accessibility problems) and technical requirements, such as the roof's load-bearing capacity, the slope, and the amount of accessible solar radiation. The data presented in this work can be an important step in developing tools in future applications regarding the development of sustainable cities.

Chapter 5

Assessment of the food-water-energy nexus suitability of rooftops. A methodological remote sensing approach in an urban Mediterranean area

CHAPTER 5 - Assessment of the food-water-energy nexus suitability of rooftops. A methodological remote sensing approach in an urban Mediterranean area

This chapter is based on the following journal paper[2]

Zambrano-Prado, P., Munoz-Liesa, J., Josa, A., Rieradevall, J., Alamús, R., Gasso-Domingo, S., & Gabarrell, X. (2021). Assessment of the food-water-energy nexus suitability of rooftops. Methodological remote sensing approach in a urban Mediterranean area. Sustainable Cities and Society, 103287. https://doi.org/10.1016/j.scs.2021.103287

Abstract

This work established a framework to identify and analyze the technical feasibility of roofs for integrating urban agriculture, rainwater harvesting, and photovoltaic systems using various remote sensing. The framework was applied to a Mediterranean region north of Barcelona. Both commercial and nonprofit urban agriculture purposes were considered, and three levels of solar access requirements for tomato, leafy crops, strawberries, and microgreens were established. The case study included compact and disperse urban forms, residential and nonresidential building uses and various building typologies. It was identified that 8% of the roof area is feasible for tomato and lettuce production, and production could satisfy the 210% of average intake of tomatoes and the 21% average yearly consumption of lettuce. Rainwater harvesting systems could supply 94.26% of the water requirements for lettuce growing in an open-air system; in contrast, 53% of irrigation could be satisfied for tomato production in rooftop greenhouse systems. The results showed a potential for 80% of roof area to be used for rainwater harvesting systems, representing the average yearly water consumption of 44% of citizens for laundry, showering, toilet flushing, cleaning and irrigation uses. Finally, 50% of the roofs are suitable for photovoltaic panels, representing an average energy consumption of 18% of citizens.

Keywords

Rooftop urban agriculture, rainwater harvesting, solar energy, self-sufficiency, geographic information systems, remote sensing

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[2] Journal pre-proof status when this thesis was finished

5.1 Introduction

Cities cover about 1% of the surface area on the planet and house about 55% of the world's population (almost 75% in Europe). With increased urbanization, the proportion of the world's population living in cities is predicted to rise to 70% globally by 2050, and up to 85% in Europe (European Investment Bank, 2018). Urban areas that are functional as centers of production, consumption, and human settlement contain a variety of vital driving forces for social, economic, and environmental stability and sustainability (N. Bin Chang et al., 2020). Cities consume about 70% of global resources and emit 70% of all greenhouse gases (European Investment Bank, 2018) which generates environmental, social and economic consequences. Food, water, and energy security have become pressing concerns, to supply these essential needs, cities must depend on their hinterlands (McGranahan & Satterthwaite, 2003), rendering cities unsustainable. Food, water, and energy demand are expected to increase by more than 50% in 2050 (International Renewable Energy Agency, 2015). In this context, cities must improve resource management through sustainable urban planning strategies (Bibri & Krogstie, 2017) considering the food-water-energy (FWE) nexus.

5.1.1 The nexus between FWE and land in cities

Food production requires energy (and water) in many stages of the food system. Energy is necessary in irrigation systems, farm machinery, fertilizer production, greenhouse heating and cooling, packing, transportation and distribution (FAO, 2015; Midgley et al., 2019). Energy is required to extract, pump, lift, collect, transport and treat water. The agri-food sector consumes 30% of the world's energy (FAO, 2016). According to projections, by 2050, the demand for energy will double globally (International Renewable Energy Agency, 2015). Energy inputs into the food supply chain are likely to increase in the coming decades, leading to increased energy production necessities (FAO, 2016; International Renewable Energy Agency, 2015).

Nowadays, 24% of total freshwater consumption exceeds the regional capacities (Motoshita et al., 2020), producing consequences such as water resource overexploitation, stress, and scarcity (Campisano & Modica, 2015; Gosling & Arnell, 2016). In addition, climate change has negative repercussions for water cycles (Arnell & Gosling, 2016; Gosling & Arnell, 2016). Water is also needed during the production processes of energy required for water abstraction, distribution, and treatment, as well as food production and distribution processes. In addition, indirect water plays an important role on farm machinery, fertilizer production, packing, transportation processes.

Agriculture consumes 70% of water worldwide (International Renewable Energy Agency, 2015). As the largest consumer of freshwater resources globally, agricultural practices have substantial impacts on water security. Agricultural contamination remains a major source of water pollution. Different agricultural activities, such as fertilization, manure spreading and irrigation, have impacts on surface water and groundwater; for example, approximately 70% of the water pollution in China comes from agriculture in the form of runoff from fertilizers, pesticides and animal waste (International Renewable Energy Agency, 2015).

Land is also an important resource concerning the FWE nexus and is a finite resource needed for food production and some forms of energy (e.g., wind and solar farms) and water (e.g., catchment areas, water supply infrastructure and ecosystem services) (FAO, 2015; Midgley et al., 2019). Agriculture already uses 12% of the world's land surface for crop production (FAO, 2011). Moreover, the use of some of these areas for the agriculture sector would compromise valuable ecosystem services and biodiversity (FAO, 2011).

The production of local resources in cities is a key strategy to ensure the resilience of and accessibility to food, water, and energy. In the case of food systems, urban agriculture (UA) is an approach to satisfying food demand in cities, with advantages in different fields, such as social (e.g., social inclusion), environmental (e.g., transport emissions reductions) and economic impacts (Lupia et al., 2017; Mok et al., 2014; Parece et al., 2016; Thomaier et al., 2015). In addition, rainwater harvesting systems (RWHSs) are strategies for managing water resources, providing sustainable water cycles and minimizing water tap demand (Jha et al., 2014; Sojka et al., 2016). Regarding the energy sector, bioenergy, solar photovoltaic (PV) or solar thermal panels can satisfy a relevant part of energy demands (Corcelli et al., 2019; Midgley et al., 2019).

In urban areas, land is an increasingly scarce resource, and the high price and competition for residential buildings, industrial growth or infrastructure construction represent some of the main threats to the local production of food, water, and energy (Benis et al., 2018a; Midgley et al., 2019). In this sense, since rooftops cover half of the impermeable surfaces in cities (Farreny et al., 2011), there are many areas that could be potential spaces for producing food (e.g., through the installation of open-air agriculture or rooftop greenhouses (RTGs)), water collection (e.g., rainwater harvesting systems) and energy (e.g., solar photovoltaic or solar thermal panels).

5.1.2 Rooftops as productive spaces

Rooftops have the potential to improve urban metabolism by producing resources (for instance, food, water, and energy) (Corcelli et al., 2019). In the case of promoting local food production, the environmental benefits are mainly related to a reduction in transportation requirements and the consequent environmental impacts (Cerón-Palma et al., 2012; Sanyé-Mengual et al., 2013). The transformation of rooftops into productive spaces is becoming a common practice in many cities worldwide (Gundula Proksch, 2016) New York, Paris, Vancouver, Toronto, Barcelona and Melbourne are some of the cities that have started to convert roofs into potential productive spaces, integrating food production and solar photovoltaic and solar hot water systems (City of Toronto, 2009; The New York City Council, 2010; Ville de Paris, 2019).

Different criteria must be considered to assess the feasibility of integrating FWE systems. Climatic conditions are crucial to determining the potential integration of FWE systems. For food production, sunlight access is the main climate parameter for determining the suitability of rooftop urban agriculture (RUA), based on the requirements of the selected horticultural crop (FAO, 2013). Regarding the integration of RWHS, it is necessary to consider the rainwater potential, which refers to the entire amount of rainfall in the area under consideration (Worm & van Hattum, 2006). Solar energy, as in the case of RUA, requires solar radiation on rooftops, and shadows from the built environment play an important role in identifying potential areas.

Roof characteristics, such as their geometry, area, slope, solar radiation and materials, also need to be considered. Additionally, climatic conditions are determinant factors for assessing the suitability for integrating food, water, or energy production systems in cities (Carter & Keeler, 2008; Orsini et al., 2016; Salvador et al., 2019; Toboso-Chavero et al., 2018; Villarreal & Dixon, 2005). In the following section, the literature concerning roof characterization using remote sensing (RS) to assess the potential integration of FWE systems is described.

5.1.3 Remote sensing data to assess rooftops for FWE production

Remote sensing has been utilized to assess the feasibility of roofs to implement FWE systems. Roof data acquired using light detection and ranging (LiDAR) sensors have been applied to assess the UA, RWHS, or PV potential of roofs. LiDAR systems allow us to obtain geometric data and to compute solar access to roofs. Table 1 illustrates a summary of works assessing UA, RWH, and PV potential on roofs using remote sensing data

Table 5.1. Characterization of rooftops using remote sensing and geographic information systems to integrate UA, RWH, or PV.

Resource production	Scale of study case	Data collection and GIS technique used	Software	Building use							Roof data acquired with remote sensors						Reference
				C	I	R	E	I	Re	W	A	S	SD	M	BF	BH	
F	N	Building footprint solar map from LiDAR	ArcGIS	•	•						•	•	•		•		Berger (2013)
F	Ci	Land use map Google Earth	ArcMap		•						•						Haberman et al. (2014)
F	Ci	DSM from LiDAR	ArcMap	•	•	•					•	•				•	Saha & Eckelman (2017)
F	Co	DSM from LiDAR; spectral signatures from LWIR data	QGIS		•						•	•	•	•			Nadal et al. (2017)
W	Co	Aerial imagery LiDAR data	Esri	•	•	•					•						Grant et al. (2017)
W	Ci	Satellite image DEM from LiDAR	QGIS			•				•	•						Lupia et al. (2017)
W	N	Building footprint from satellite imagery	ArcGIS	•		•	•				•			•			Radzali et al. (2018)
E	Ci	DSM from LiDAR	ArcGIS	•	•	•		•	•		•		•				Bayrakci Boz et al. (2015)
E	Ci	DSM from LiDAR	ArcGIS			•	•	•			•		•				Brito et al. (2012)
E	N	Google Earth satellite imagery	ENVI EX	•		•		•			•		•				Khan & Arsalan (2016)
E	Co	Building footprint from LiDAR	Not specify	•		•					•		•				Kodysh et al. (2013)
E	Ci	Aerial imagery	ArcGIS			•					•		•				Wiginton et al. (2010)

Resource production: food (F), water (W), and energy (E). Scale of the studies: city (Ci), county (Co), and neighborhood (N). Building use: commercial (C), industrial (I), residential (R), educational (E), institutional (I), recreational (Re), and warehouse (W). Roof data acquired with remote sensors: area (A), slope (S), solar radiation (SD), material (M), building floors (BF), and building height (BH).

Previous works using remote sensing for data acquisition focused on a single vector food, water or energy (Table 5.1). Toboso-Chavero et al. (2018) assessed the potential integration of the FWE nexus on residential buildings. Architectural and urban requirements were based on the methods adapted by Nadal et al., (2017). However, roof data acquisition was conducted by means of architectural layouts, implying difficulties for the application at larger scales, such as counties or cities (Toboso-Chavero et al., 2018). The method proposed by Nadal et al., (2017) uses GIS and RS to obtain and manage information to identify suitable roof areas on industrial roofs for commercial UA. In this sense, there is a need to assess the viability and potential roofs for the assessment FWE production from an integrated framework, based on the acquisition of urban and architectural data using remote sensing technology.

Most of the studies considered residential, industrial, and commercial buildings to integrate UA, RWHS or PV systems. Especially for RUA integration, industrial followed by commercial buildings have a greater presence in previous studies. In addition, large surfaces (minimum 465 and 500 m^2) have been considered for commercial purposes (Berger, 2013; Haberman et al., 2014; Nadal et al., 2017; Salvador et al., 2019; Sanyé-Mengual et al., 2016; Sanyé-Mengual, et al., 2015a). To a lesser extent, studies have been carried out for self-consumption purposes considering smaller roof areas and educational and housing roofs (Nadal et al., 2019; Nadal et al., 2018; Saha & Eckelman, 2017). Non-profit UA spaces can provide educational and self of belonging functions. UA in schools, for example, provides environmental education and social cohesion, and according to the main goal of the Global Education 2030 (Agenda UNESCO), it is necessary to acquire sustainability competencies as a core of Education for Sustainable Development (Leicht et al., 2018). However, no methodological framework has been found that meets both commercial and self-consumption purposes.

Roof material criteria is rarely considered to assess the potential of UA, RWHS or PV systems (Table 5.1).The knowledge of roof materials is valuable as an indicator of the construction systems and their load-bearing capacity to support the weight of FWE systems (Sanyé-Mengual et al. 2015a; Nadal et al. 2017). Besides, the quality and quantity of rainwater harvested from roofs are significantly affected by roofing materials (Farreny et al. 2011). However, the process of acquiring rooftop data is complex, laborious, and time-consuming since a detailed database to analyze (Nadal et al., 2017). In addition, data collection through site visits or visual interpretation may limit the scale to be analyzed. Hyperspectral imaging data acquired using Long Wave Infrared (LWIR) remote sensor has resulted fast, automated and digital tool for identifying roofs characteristics (Nadal et al., 2017). However, it has been suggested that the use of two or more sensors operated simultaneously with different spectral ranges, can improve discrimination of materials in urban contexts (Roberts et al., 2012).

5.1.4 Sunlight access for rooftop urban agriculture

Another important aspect refers to sunlight access which has received little consideration in the literature, referring to the assessment of UA on rooftops. This criterion is critical for growing food. Solar radiation is a fundamental energy source for photosynthesis which ultimately affects crop yields. The cumulative measurement of total daily photons reached by plants is known as daily light integral (DLI) expressed in mol/m^2/day, and explains the linear relationship between light and plant growth rate needed to saturate the leaf net photosynthetic rate (Kozai et al., 2015). DLI requirements vary depending on the crop and its photoperiod, which range between 6 to 35 mol/m^2/day. However, current methods to identify potential roofs for UA areas normally define a target DLI value between 20 – 25 mol/m^2/day (originally expressed in MJ/day,. Nadal et al., 2017; Sanyé-mengual et al., 2015a). Another study assumed that roof area suitable for PV is also suitable for UA (Berger, 2013).

DLI target usually satisfies light requirements for single species, usually tomato crops (Benis et al., 2017b; Nadal et al., 2017; Sanyé-mengual et al., 2015a). Compared to the optimal DLI crop requirements (see Supporting Information 2.4 Table 3), this is a high threshold that results in over-energy lighting needs in the majority of crops (Benis et al., 2017b), leading to high environmental costs derived from LED systems. Thus, high DLI targets also underestimate the urban potential area that could grow low and medium-DLI crop types.

In this context, the novelties of this approach are the integration of additional urban and architectural requirements to existent methods, the consideration of FWE systems, the use of two hyperspectral remote sensors with a high spatial resolution (as a basis for data acquisition), and the classification of optimal daylight needs for crops in both RTGs and open-air systems.

5.1.5 Objectives

The main objective of this study is to assess the feasibility of roof areas to integrate food production, rainwater collection, and solar energy systems in cities using remote sensing technologies. In this regard, the specific objectives are 1) to establish a framework for evaluating the potential integration and self-sufficiency of FWE systems for commercial and nonprofit purposes; and 2) to apply the procedure in a Mediterranean area.

5.2 Materials and methods

5.2.1 Case study

The case study is located in a Mediterranean region in the El Vallès Occidental, north of the Spanish city of Barcelona. The Vallès Occidental is composed of 23 municipalities, and some of them are part of the Metropolitan Area of Barcelona (MAB). This area was chosen due to its sunny weather predominance, which offers a strong potential to integrate both RTGs, open-air rooftop agriculture and solar energy systems. This climatic area can also offer winter crop production without requiring any active system to heat greenhouses. There are recent initiatives from the city council to promote productive roofs and institutional and citizen awareness of UA. Additionally, the case study area includes a pilot RTG at the Institute of Environmental Science and Technology (ICTA) and the Catalan Institute of Paleontology (ICP) building, where different types of crops have been produced since 2015 by the Fertilecity project team (Fertilecity, 2018). Regarding rainwater, several municipalities started to approve water-saving regulations (Domènech & Saurí, 2011), including RWHS, since the amount of precipitation makes the integration of these systems in this area suitable.

5.2.2 Criteria to integrate FWE systems for commercial and nonprofit purposes

The work developed by Nadal et al. (2017) and Toboso-Chavero et al. (2018) was used as a basis for developing the methods of this work and adding other aspects obtained from the literature (see Supporting information 2.1. Criteria to integrate FWE systems for commercial and non-profit purpose). The previous authors considered in their methods the short-term potential implementation of the systems on industrial and residential rooftops. The work developed by Toboso-Chavero et al. (2018) assessed the potential integration of the FWE nexus. However, roof data acquisition was conducted by means of architectural layouts, implying difficulties for the application at larger scales, such as counties or cities. The methodology proposed by Nadal et al., (2017) uses GIS and remote sensing to obtain and manage information to identify suitable roof areas. However, it only focuses on RTGs on industrial roofs for commercial purposes. In this regard, both methods present a lack of some criteria for assessing the potential of integrating FWE systems for commercial and nonprofit purposes. For this reason, a literature review was performed to detect and establish the needed criteria to broaden the focus of the framework for this work. Figure 5.1 summarizes the phases of the methods used for this work: phase 1 study area characterization was based on the work developed by Toboso-Chavero et al. (2018) and enhanced with a literature review. Phase 2 urban and architectural requirements, and phase 3 self-sufficiency indicators were based on Nadal et al. (2017) and extended with a literature review.

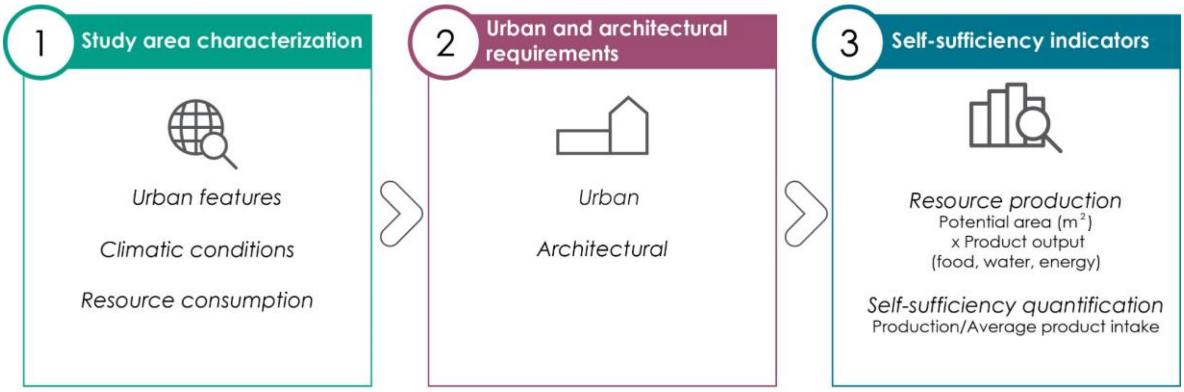

Figure 5.1. Phases to evaluate the feasibility of roof areas to integrate food production, rainwater collection, and solar energy systems in cities based on Toboso-Chavero et al. (2018) and Nadal et al. (2017).

5.2.3 Development of the framework

Figure 5.2 illustrates the framework developed to identify feasible roof areas to integrate food, water, and energy systems in cities. It is divided into three phases: study area characterization (Phase 1), urban and architectural requirements (Phase 2), and self-sufficiency indicators (Phase 3). Figure 5.2 also shows the methods for data acquisition for each criterion, mainly based on RS. Each of the phases is described below (for more information see Supporting information 2.1. Criteria to integrate FWE systems for commercial and non-profit purpose

Phase 1 Study area characterization. In this phase, the characteristics of the study area are obtained. Phase 1 is divided into the following three steps:

a) Urban features. GIS is used to define the boundaries and to conduct a spatial analysis. Data about population density, at the county, city, or neighborhood level, depending on the scale of the study area. Urban form, building use, and building typology are needed to conduct a spatial analysis. Population density was acquired at municipality level from a public dataset. Roof area, land use, use and typology of buildings is acquired using GIS. Urban form is acquired using a literature review, and GIS information. To identify land use and building typologies, two vector layers were used: (1) The Urban Planning Map of Catalonia (UPMC), downloaded free from the Department of Territory and Sustainability (2019), and (2) roof polygons obtained from a previous work developed by the authors. Data from these two layers were integrated using the tool join attributes by localization.

b) Climatic conditions. Since climatic conditions play an important role regarding the potential of FWE systems, a minimum solar radiation of 1,000 MJ/m^2/year is needed for food production (microgreens) in open-air systems and a minimum of 300 mm/year of rainfall. To obtain this information, datasets from public websites are used. The rainfall dataset was obtained from a weather station (Rural Cat, 2019) over a period of 21 years (from 1996 to 2017). The average annual solar radiation was obtained from an atlas of solar radiation in Spain (Sancho et al., 2012).

c) Resource consumption. Food, water, and energy consumption are needed to determine the resource quantity required and used in phase 3. Both datasets and a literature review are used to obtain resource consumption information.

Food, water, and energy demand was acquired from regional and local public reports (Ajuntament de Barcelona Medi Ambient i Serveis Urbans, 2016; Departament d'Agricultura Ramaderia Pesca i Alimentació, 2017; Medi Ambient i Serveis Urbans-Ecologia Urbana Agència d'Energia de Barcelona, 2019).

Phase 2 Urban and architectural requirements. This phase is divided into two steps and various criteria by each step. For the architectural step, shows the minimum requirements needed to integrate FWE systems.

a) Urban requirements. Building laws and land uses must be considered to ensure that the new infrastructures meet legal requirements. Limitations and regulations regarding urban aesthetics for the implementation of the infrastructure must be reviewed. These data are obtained using a literature review of urban and architectural codes of the city. It is important to know the building use to establish the purpose of the infrastructure. Two purposes are proposed: commercial and nonprofit (for self-consumption and including educational and social objectives). Retail and industrial buildings are more suitable options for commercial buildings, while residential buildings, schools, and public services buildings are desirable for nonprofit goals.

To address legal requirements, Barcelona Metropolitan General Plan regulations and building codes (Metropolitan area of Barcelona, 2018) were consulted. Building uses were identified from the layers explained previously in section a) *of Phase 1: Study area characterization*.

b) Architectural requirements. This step considers four criteria: area, slope, solar access, and roof material. The first three (geometric characteristics) were acquired using a LiDAR sensor, and the last one was acquired using hyperspectral remote sensing. Each of the criteria is described below.

Roof area. A minimum roof area is needed for food and energy purposes. For commercial energy infrastructures, a minimum of 100 m^2 is needed, and in the case of food production, a minimum of 500 m^2 is required. With respect to nonprofit goals, energy systems require a minimum of 24 m^2, and food systems require a minimum of 13 m^2.

Roof slope. This criterion is divided into two: if the roof is flat with a maximum slope of 10%, food production systems can be integrated; if the roof slope is greater than 10%, energy and rainwater harvesting systems can be implemented.

Solar access. This criterion is divided into four groups, one for energy systems, in which a minimum of 1,900 MJ/m^2/year is needed, and three for food production, according to the crop and food production system. The three levels are high, medium, and low for tomatoes; leafy vegetables, strawberries, and seedlings; and microgreen crops, respectively. Each level of solar access is divided into two corresponding food production systems: RTGs and open-air. Therefore, the minimum requirements of solar access for food systems are as follows: tomatoes growing in RTGs at 3,800 MJ/m^2/year and those growing in open-air at 2,000 MJ/m^2/year; leafy vegetables, strawberries, and seedlings cultivated using RTGs at 2,800 MJ//m^2/year and those using open-air at 1,650 MJ/m^2/year; and microgreens produced in RTGs at 1,400 MJ/m^2/year and those produced in open-air at 800 MJ/m^2/year (see Supporting information 2.4. Light conversion factor). In this work, priority was given to roofs with high radiation levels for the integration of greenhouses. These infrastructures have the advantage of greater climate control in addition to a higher production of the crop. These infrastructures have the advantage of greater climate control in addition to a higher production of the crop. When the integration of urban agriculture was possible, solar energy was not considered because current panels diminish light for crops. It was demonstrated that transparent photovoltaic (TPV) panels are not yet developed for commercialization (K. Lee et al., 2020).

Roof material. The load-bearing capacity to support the weight of the system is essential, and a minimum load-bearing capacity of 200 kg/m^2 is required for crops. A lower capacity can be suitable for energy systems. The load capacity of the roof does not condition rainwater collection in this sense, and any material has potential for water systems with special attention paid to health risks according to roof materials and the future use of water resources. It is necessary to consider the part of the building in which the storage tank will be located. If the tank is placed on the roof, load-bearing must be considered. This framework does not consider water location and weight tank.

Geometric and solar radiation characterization. LiDAR remote sensing technology was used to characterize the geometric properties of roofs. Then, solar irradiation on surfaces was computed with GRASS software, version 7.4. This process considered all of the shadow effects in the surrounding area. The airborne sensor Leica ALS50-II (LiDAR) was used on a flight conducted in 2013. Based on high density (4 points/m^2), a digital surface model (DSM) with a spatial resolution of 0.5 m pixels was obtained. This model contained all of the geometric characteristics of the terrain and buildings, such as area and slope. The model also included objects on rooftops (e.g., air conditioning installations) and objects that can produce shadows over roofs. The point cloud was classified as ground, vegetation, buildings, and other objects that were not rooftops. Then, points that were considered noisy, such as powerline wires, points with low intensities, and points in the air, were excluded. The average annual solar irradiation was computed with the r.sun library in GRASS software, version 7.4, by adding direct and global radiation received at each pixel of the DSM every hour for one day of each week over the whole year. In this calculation, all of the shadows generated by buildings, vegetation, topographies, etc., were considered.

Roof material characterization. Previous work about roof mapping developed on chapter 4 was used. In this work, two classes of roofs were totally excluded to integrate FWE systems. Fiber cement roofs were excluded because of their low load-bearing capacity to support RTGs, open-air UA, and PV panels, as well as health risks for collecting rainwater; additionally, green roofs were excluded considering that they are already productive spaces. It should be noted that the location and weight of the water tank for RWHS were not considered in this work.

Data layers with geometric characteristics (area and slope) and nongeometric characteristics (solar radiation, roof materials, use and typology of buildings) were integrated into a single GIS layer with QGIS software using the *joint attributes by location* tool. Once all of the data were integrated into a single layer, potential roofs were identified using *select by expression* tool. With this tool, roof requirements for each system (food, water, and energy) were filtered and then extracted into a new layer of roof polygons that fully fit the established criteria. In this work, potential areas for food production were prioritized with respect to energy production.

Phase 3 Self-sufficiency indicators. This phase is divided into two steps: resource production and self-sufficiency potential. Food production consists of a variety of systems and methods for growing crops that affect growing values and water requirements for irrigation; in the case of RWH, the quantity of rainwater harvested from roofs is affected by roofing materials; and for photovoltaic systems, solar radiation influences the amount of energy produced. Thus, the first step uses different equations, in which the total roof area that fulfils the criteria for phase 2 identified as potential and other parameters are used to obtain the production per year of food, water or energy. In the second step, self-sufficiency potential uses results derived from the first step and consumption of resource data to obtain how many people can be supported by the food, water, or energy supplied.

a) Resource production. Tomatoes and lettuce were considered suitable crops due to the amount of household consumption data in the region of the case study. Tomatoes were chosen because they are the second most consumed vegetable in Barcelona, after potatoes (Departament d'Agricultura Ramaderia, Pesca i Alimentació, 2017), which cannot be produced in hydroponic RTG systems. Lettuce represents the most consumed leafy vegetable (Departament d'Agricultura Ramaderia, Pesca i Alimentació, 2017). For the calculation of production intercrops were not considered. Soil-less systems for both open-air and RTG conditions were taken into consideration. Food-crop yield was obtained for RTGs and open-air studies from Barcelona. Average yield values are listed in the Supporting information 2.2. To calculate the rainwater harvesting potential, runoff coefficients of 0.80 (ceramic), 0.90 (metals), and 0.60 (gravel) were considered (Farreny et al., 2011) according to roof materials in the study case. Multicrystalline silicon (multi-Si) technology was chosen for PV because it is the most common in the market (Paiano, 2015) for estimating energy production, and a PV panel efficiency (new) of 26% was considered (K. Lee et al., 2020).

To determine the potential production of food, water, or energy, the feasible roof area (m^2) for each system obtained from the application of the framework (Phase 2) was used in the following equations:

To quantify food production, Equation 5.1 was used, where FP is the yearly food production (kg), $\sum a$ is the total feasible rooftop area (m^2), and YV is the average yield value (kg/m^2).

$$FP = \sum a \times \mathrm{YV} \tag{5.1}$$

To determine the water harvesting potential, Equation 5.2 was used, where WHP is the yearly amount of rainwater harvested from rooftops (L), $\sum a$ is the total feasible rooftop area (m^2), P_{tot} is the total annual precipitation (mm), and RC is the runoff coefficient (harvesting efficiency of the system, depending on roof material; see above).

$$WHP = \sum a \times P_{tot} \times RC \tag{5.2}$$

To determine solar energy production, Equation 5.3[3] was used, where $PVEP$ is the yearly amount of photovoltaic energy production ($kWh/m^2/year$), $\sum a$ is the total feasible rooftop area (m^2), and SR is the global solar radiation potential (kWh/year).

$$PVEP = \sum a \times SR \tag{5.3}$$

[3] The equation already considers the system characteristics described above.

b) Self-sufficiency. Fresh tomato and lettuce consumption of 14.9 and 4.4 kg/per capita/year, respectively, was considered (Departament d'Agricultura Ramaderia Pesca i Alimentació, 2017). Water consumption of tomatoes and lettuce production in Barcelona in open-air and RTG systems and the soil-less method were considered for calculations of water self-sufficiency for irrigation crops (see Supporting information 2.3. Water requirement for tomatoes and lettuce irrigation). In addition, the water demand for domestic use was acquired from the El consum d'aigua a Barcelona L'aprofitament i els usos dels recursos hídrics (water consumption in Barcelona The use of water resources) report, considering an average of 105 L/household/day, including laundry, showering, toilet flushing, cleaning and irrigation (Ajuntament de Barcelona Medi Ambient i Serveis Urbans, 2016). The average yearly energy consumption over a period of 19 years was estimated from data obtained from the Balanç d'energia amb efecte d'hivernacle i emissions de gasos de Barcelona 2017 (Energy Balance and Greenhouse Gas Emissions of Barcelona 2017) report (Medi Ambient i Serveis Urbans-Ecologia Urbana Agència d'Energia de Barcelona, 2019).

To determine the potential of self-sufficiency (# persons), the following equations were used.

To quantify potential food self-sufficiency, Equation (5.4) was used, where $PFSS$ is the self-sufficiency of total food production, FP is the food production (obtained from Equation 5.1), and FD is the average food demand (kg/per capita/year).

$$PFSS = \mathrm{FP}/\mathrm{FD} \tag{5.4}$$

To quantify potential water harvesting self-sufficiency, Equation (5.5) was used, where $PWSS$ is the self-sufficiency of the total water collection of roofs, WHP is the water harvesting potential (obtained from Equation 5.2), and WD is the average water demand (L/per capita/year).

$$PWSS = \mathrm{WHP}/\mathrm{WD} \tag{5.5}$$

To quantify potential solar energy self-sufficiency, Equation (5.6) was used, where $PESS$ is the self-sufficiency of total PV energy production, PVEP is the total photovoltaic energy production (obtained from Equation 5.3), and ED is the average energy demand (MWh/per capita/year).

$$PESS = \mathrm{PVEP}/\mathrm{ED} \tag{5.6}$$

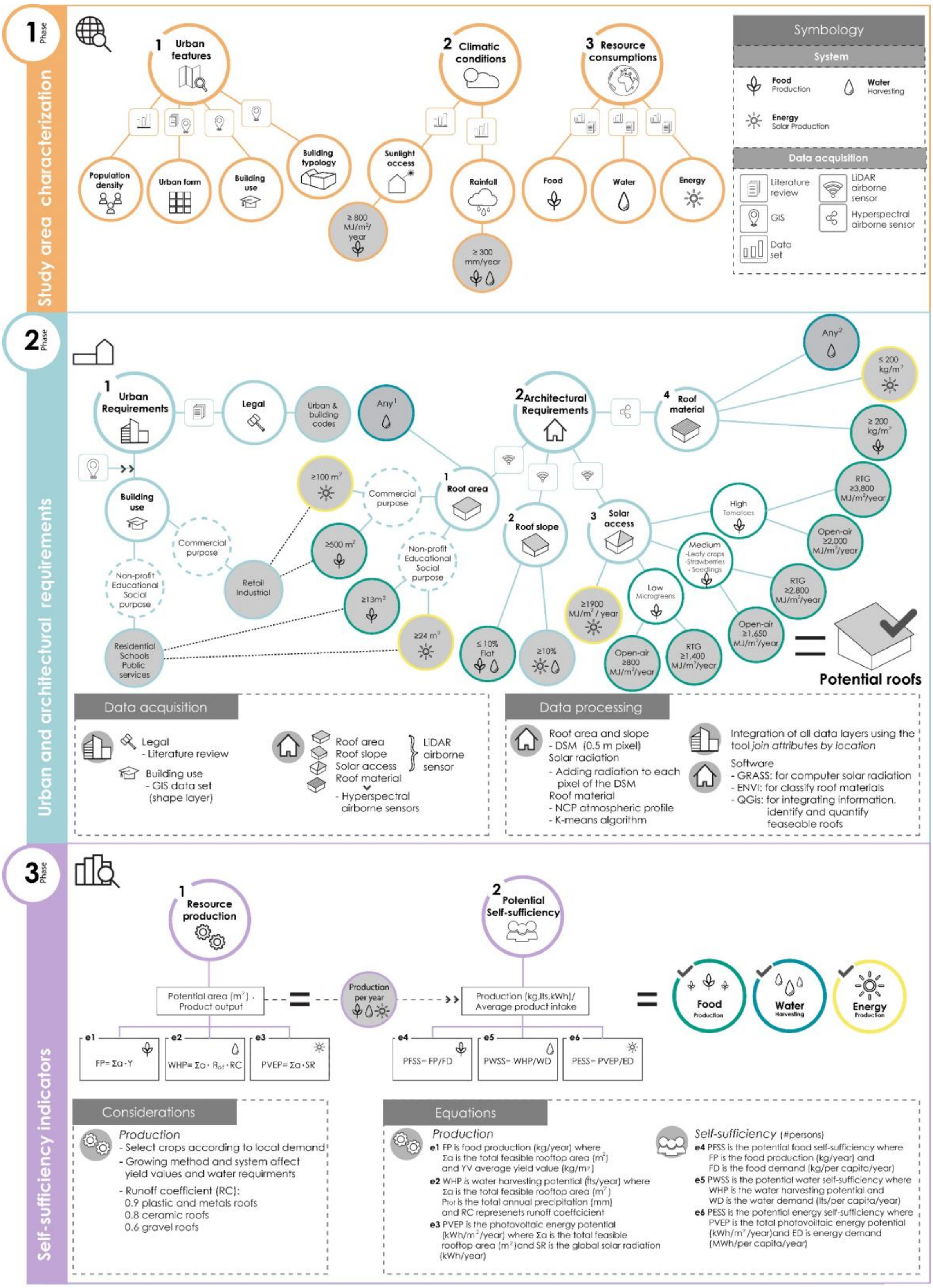

Figure 5.2. Workflow proposed to identify feasible roof areas to integrate urban agriculture, rainwater harvesting, and photovoltaic energy systems. The sunlight access criterion of the phase 1 study area characterization refers to the minimum energy radiation for producing microgreens.

5.3 Results

5.3.1 Study area characterization

Figure 5.3 illustrates the study area location in the Vallès Occidental County north of Barcelona, Spain, and its main characteristics. The study area has approximately 67,000 inhabitants and comprise 15 km^2. The population density varies in a range from 14,427 to 1,624 depending on the municipality. Compact and diffuse urban forms are presents. A total of 3 km^2 of roofs ranging from 0.25 m^2 to 13,481 m^2. Roofs were in different land uses: housing (75.0%), industrial (16.6%), services (5.9%), mix (0.6%), and non-urban (0.5%). Some roofs were not identified with respect to the land use location (1.5%). Different building typologies of housing were found: 4.3% corresponded to low rise buildings in the founding nuclei and centres populations (R1); 25.1% to compact and open building blocks, corresponding to historical growth of a structure before 1950 (R2); 0.4% to multifamily blocks with interior patios, corresponding to modern extension (R3); 12.9% to blocks or towers configured from an isolated multifamily building (R4); 38.4% to detached houses for single families (R5); 18.6% to terraced houses for single families (R6); and 0.1% to building blocks for public equipment housing (SD). The average global radiation is 4.6 kWh/m^2/day, and the average annual rainfall over the study area is 592 mm.

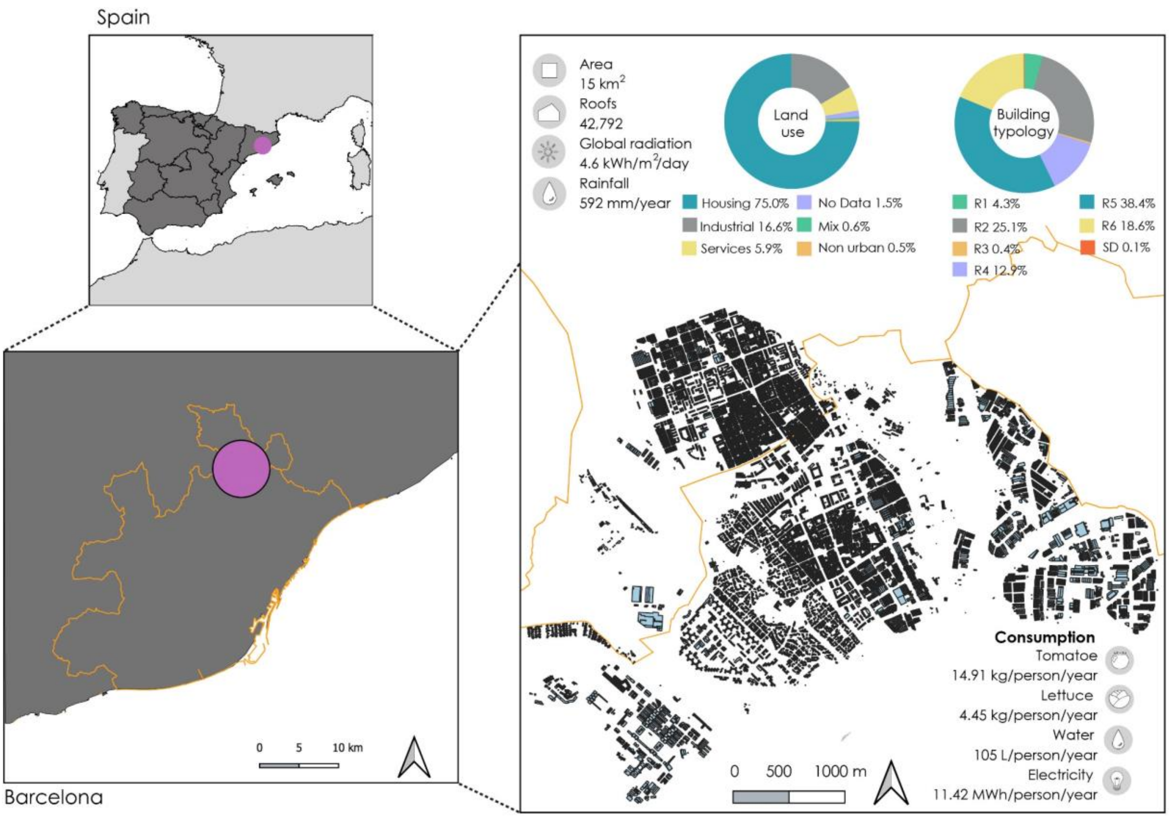

Figure 5.3. Location and study area characterization. Building typologies of housing in the study area included low rise buildings in nuclei and centre populations (R1), compact and open building blocks (R2), blocks with interior patios (R3), isolated blocks or towers (R4), detached houses (R5), terraced houses (R6), and building blocks for public equipment housing (SD).

Food production is allowed for self-consumption. Land use types do not include agriculture use. For this reason, UA for commercial purposes is not permitted. On some rooftops, RTGs were not permitted due to the maximum height and volume restrictions. In this sense, a case-by-case review by local technicians is required. To integrate RWHS and PV systems on rooftops, no restrictions were found. According to the Spanish Technical Building Code, it is mandatory to include minimums for electricity and sanitary hot water self-sufficiency in new buildings and developed building extensions (except for residential buildings) when the constructed area exceeds or is increased by more than 3,000 m^2.

5.3.2 Analysis and quantification of potential roofs for integrating FWE systems

After applying the proposed framework, potential roofs were obtained. In this section, the results are presented in layers according to the systems studied. A total of 38,575 roofs (2.6 km^2) representing 87% of the total roof area were identified for integrating UA, RWHS, and PV (Figure 5.4a). These results were identified by different colors according to the systems, as shown in detail in Figure 5.4b. Result showed that 8% (0.2 km^2) of total roofs identified as potential could integrate both UA systems (commercial and self-consume) and RWHS. The 50% (1.3 km^2) of potential areas could integrate PV and RWHS systems. The 42% (1.1 km^2) of feasible roofs were potential for integrating RWHS (Figure 5.4c). It can be observed that 78% of potential rooftops were residential housing, 13% industrial, 6% services buildings, mix (0.5%) and nonurban (0.3%) were recognized in similar proportion, and 1.4% of roofs did not have data about building use (Figure 5.4d). A total of 92 green roofs were detected, of which 7 roofs were identified as potential tomatoes crop using for open-air system and 9 for solar energy. These potential areas represent 0.013% for RUA and 0.016% for PV of the total roof area. As indicated in section 3 Development of the Framework, rooftops classified as *green roofs* were discarded from the analysis of potential, production and self-sufficiency.

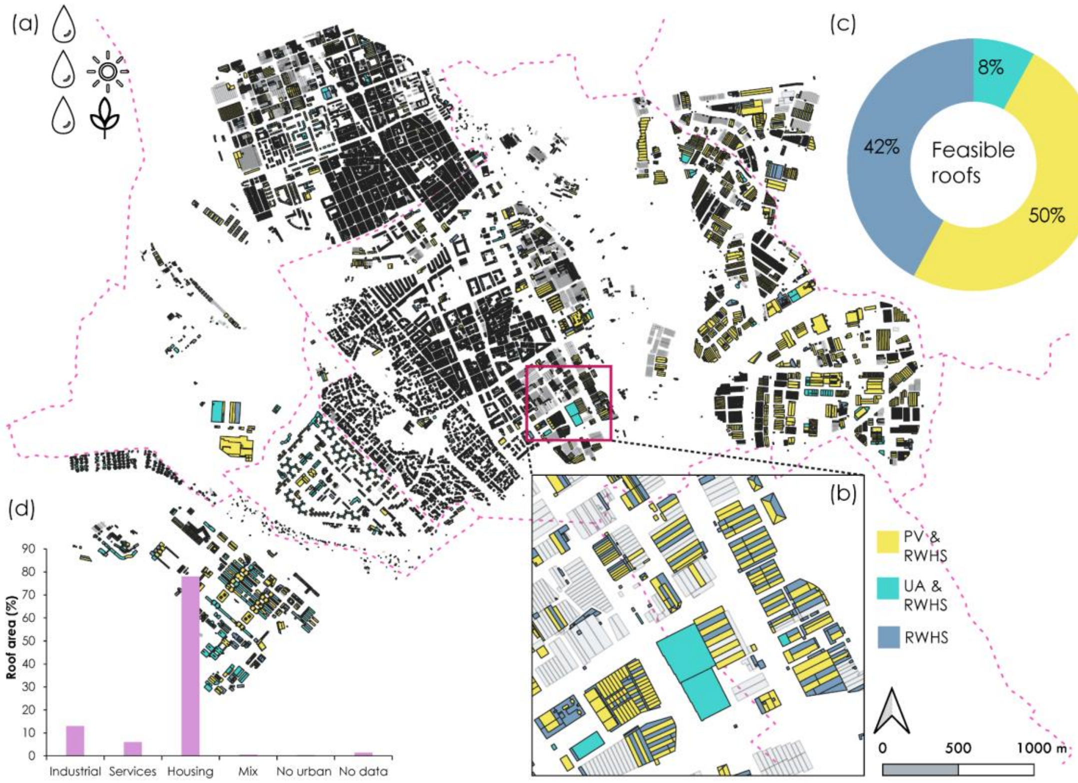

Figure 5.4. (a) Potential roofs over the study area. (b) Details of identified potential roofs on industrial and services buildings. (c) Proportion of potential roofs for PV and RWHS, UA & RWHS and RWHS.

A total of 823 roofs and 0.2 km^2 were identified for integrating UA and RWHS (Figure 5.5a). The results of potential areas were identified by different colors according to the growing system and crop type, as shown in detail in Figure 5.5b. The distribution of potential roofs for UA was as follows: RTGs for tomatoes production 100,610.5 m^2 (49.0%); RTGs for lettuce crops 7,410.2 m^2 (3.6%); open-air for growing tomatoes 97,043.25 m^2 (47.3%); and open-air for lettuce production 89 m^2 (0.04%) (see Figure 5.5c).

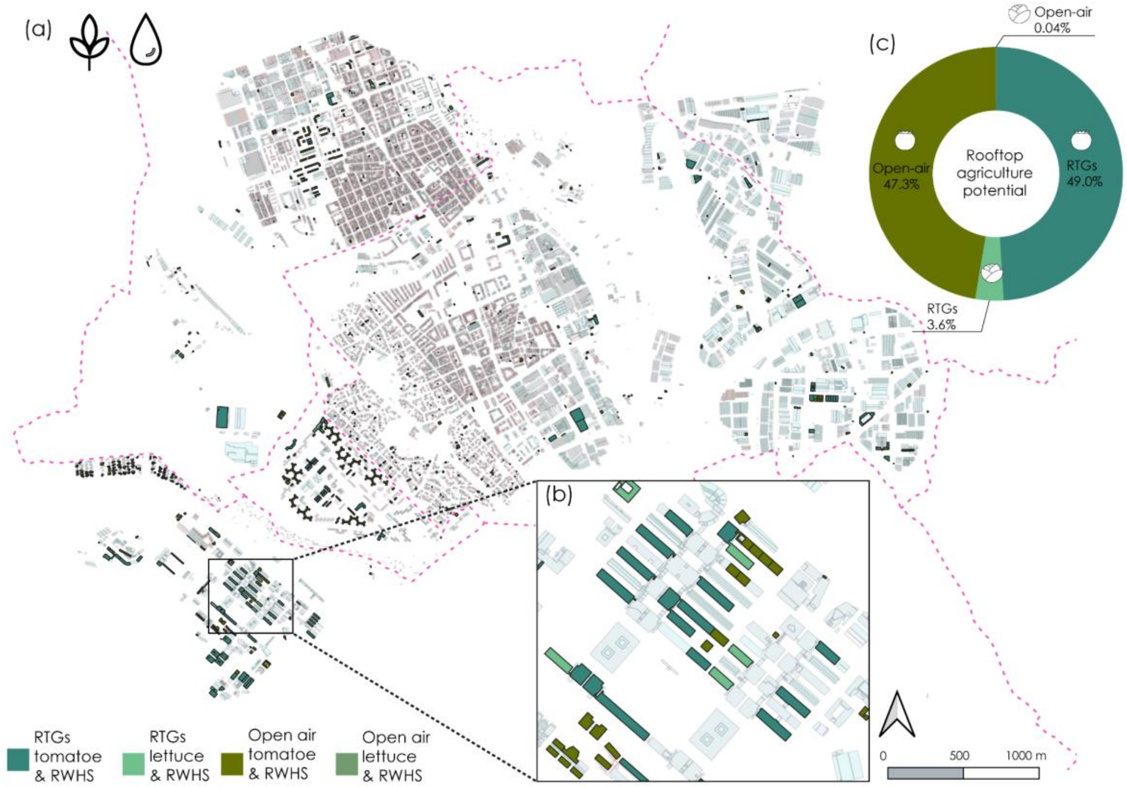

Figure 5.5. (a) Potential roofs to integrate RUA and RWHS over the total study area and distribution of roofs related to growing system and crop type. (b) Details of identified potential roofs on educational buildings from the Universitat Autònoma de Barcelona. (c) Distribution of potential roofs according to growing system and crop type.

Figure 5.6a shows potential roofs for UA and their location distribution by land use. It can be observed that most rooftops were in service land use areas. Regarding each growing system distribution of feasible rooftops according to land use, they were as follows: RTGs for harvesting tomatoes: 56.6% services, 41.5% industrial, 0.7% housing, and 1.2% mix; RTGs for growing lettuce: services 91.1% and 8.9% housing; open-air system for tomatoes: 59.4% housing, 23.4% services, 14.3% industrial, 0.4% mix, and 2.5% without data; and finally, open-air lettuce: services 68.9%, and 31.1% without data. Figure 5.6b also shows the potential roof distribution by building typology of housing use (60%). Most roofs belonged to typology R4 with 61.1%, followed by R6 with 30.1%, R2 with 6.1%, R5 with 2%, and R3 with the fewest potential roofs with 0.5%; no roofs were identified as typology R1.

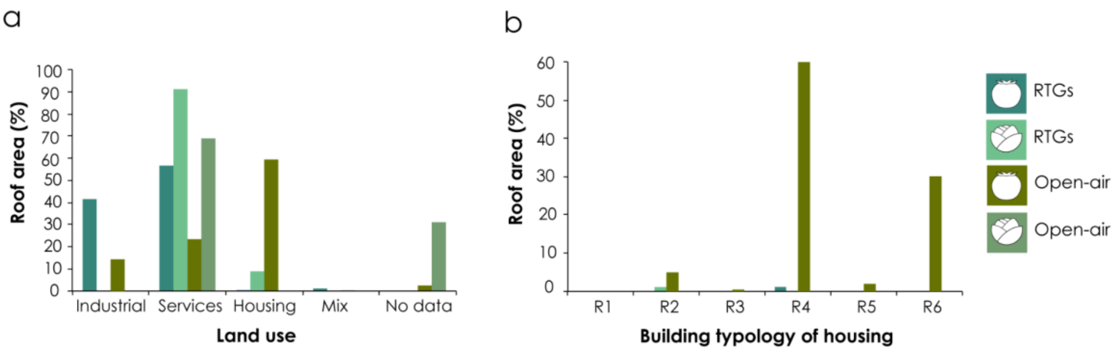

Figure 5.6. (a) Potential roofs identified to integrate RUA and their distribution by land use and (b) by building typology of housing.

Figure 5.7 shows the results of tomato and lettuce production and self-sufficiency. The total roof area for tomato crops could produce 2,096.65 tons per year, 73.4% by RTGs and 26.6% by open-air systems. Production could satisfy the average intake for 140,620 persons, representing 210% of the population over the study area (Figure 5.7). Regarding lettuce crops, the results showed that a total of 62.3 tons per year could be produced, 99.5% by integrating RTGs and 0.5% by open-air systems. This production could satisfy the consumption of 14,000 inhabitants, 21% of citizens in the study area (Figure 5.7b). Self-sufficiency analysis for crop irrigation showed that the integration of RWHS could supply 94.3% of the total water requirements for lettuce crops in open-air systems and 82.1% for the same crop in RTGs, as well as 63.2% for tomatoes in open-air and 53.0% for the same crop in RTGs (Figure 5.7c).

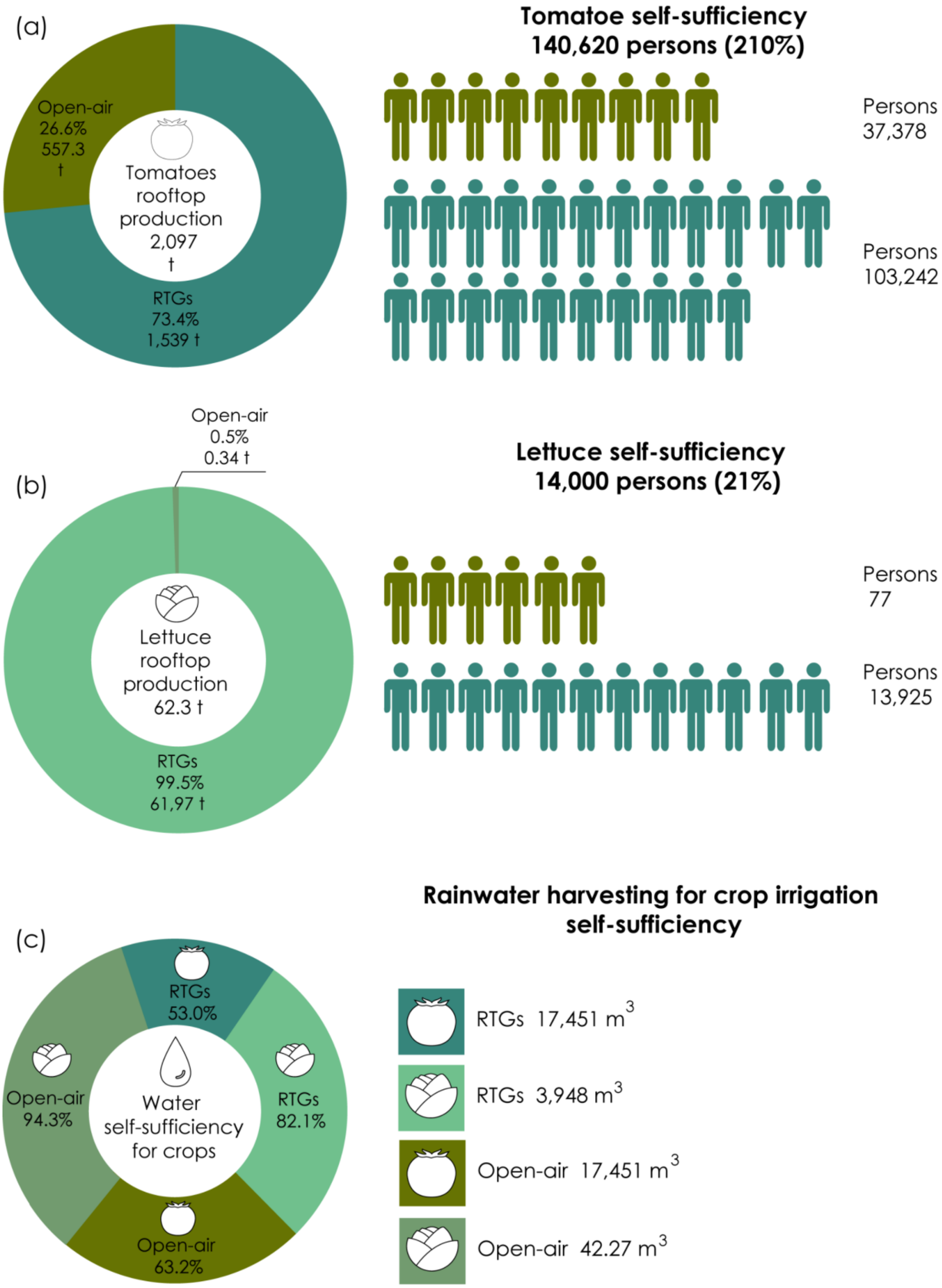

Figure 5.7. Rooftop urban agriculture production and water self-sufficiency by crop. (a) Tomato production in open-air and RTG systems and self-sufficiency. (b) Lettuce production in open-air and RTG systems and self-sufficiency. (c) Water self-sufficiency for irrigation regarding the type of crop and system. Potential roof areas for integrating UA were considered for rainwater collection for crop irrigation.

A total of 8,088 roofs and an area of 1.3 km^2 were identified to integrate PV panels and RWHS (Figure 5.8a), representing 43% of the total roofs area in the case study. Potential roofs were assigned the yellow colour. Details of the identified roofs of housing and service buildings are shown in Figure 5.8b. Roofs for PV panels were in different land uses, as shown in Figure 5.8c. Most of the rooftops belonged to industrial (65.1%); housing roofs represented 20.1%; service rooftops represented 12.6%; polygons without land use information represented 1.3%; and FWE roofs were mixed and nonurban at 0.6% and 0.4%, respectively. The results showed that a total of 140,300 MWh/m^2/year could be produced on roofs, representing the average consumption of 18% of the population in the study area (Figure 5.8d). The results showed that a total of 1,124,000 m^3 of rainwater per year could be collected on roofs (considering potential roofs from Figure 5.8 and Figure 5.9) representing the average consumption of 44% of the population in the study area for laundry, showering, toilet flushing, cleaning and irrigation uses (Figure 5.8d).

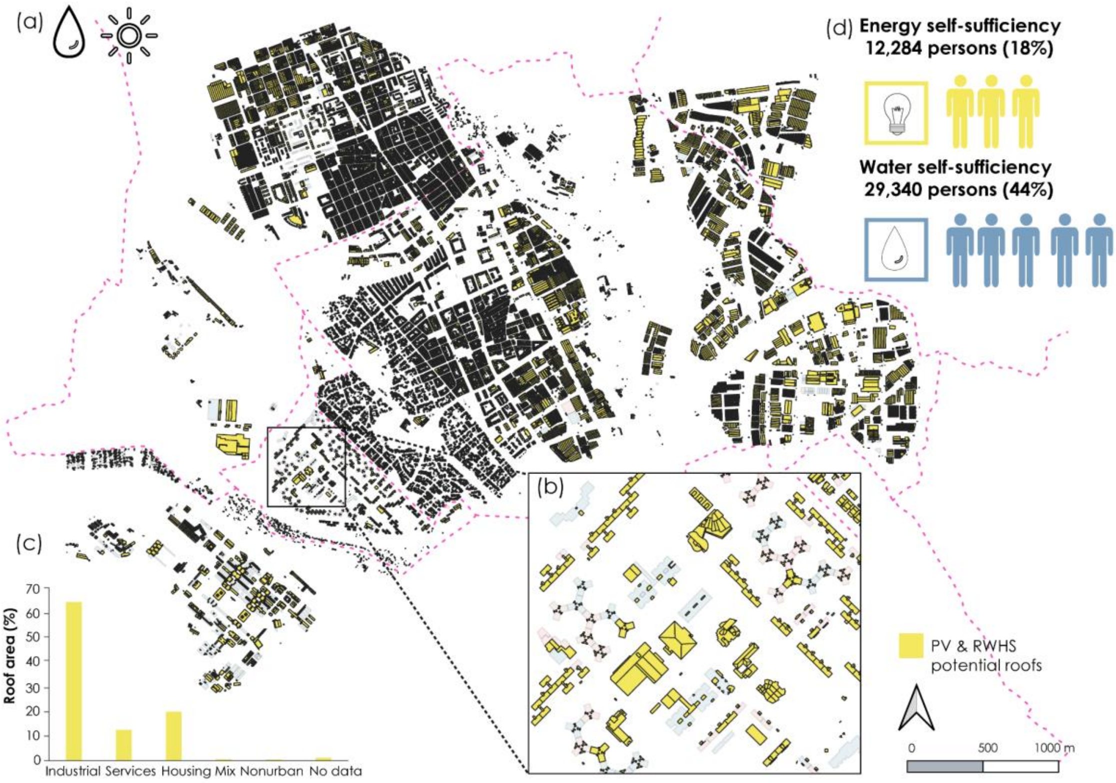

Figure 5.8. (a) Potential rooftops for solar energy production by PV panels and RWHS over the study area. (b) Details of identified potential roofs in housing and service buildings. (c) Potential roofs identified to integrate PV panels and RWHS and their distribution by land use. (d) Energy and water self-sufficiency.

A total of 1.1 km^2 of roofs were identified as feasible for integrating RWHS (Figure 5.9a). These results did not consider potential roofs for agricultural irrigation (shown in Figure 5.5a) and neither did feasible roofs for RWHS and PV (shown in Figure 5.8a). The results of potential roofs for integrating RWHS are shown in blue. Details of the identified roofs of housing and service buildings are shown in Figure 5.9b. It was identified that most rooftops belonged to industrial (43.1%) and housing (40.2%) uses; service rooftops represent 14.1%; some polygons (1.6%) did not show information related to land use; and FWE roofs were mixed and nonurban at 0.7% and 0.4%, respectively (Figure 5.9c).

Figure 5.9. (a) Potential rooftops for integrating RWHS over the study area. (b) Details of identified potential roofs in housing and services buildings. (c) Potential roofs identified to integrate RWHS and their distribution by land use. (d) Water self-sufficiency for laundry, showering, toilet flushing, cleaning, and irrigation (no agricultural) uses.

5.4 Discussion

5.4.1 Rooftop potential to integrate FWE systems and building use

In relation to feasible roofs for UA and food production, this work found that 8% of roofs in the study area could integrate urban agriculture. This result is similar to those obtained by Sanyé-Mengual et al. (2015a) in a logistic and industrial park area located in Barcelona where a 8% of roofs were found feasible for RTGs representing 13 h. Compared to Sanyé-Mengual et al., (2015a) work the feasible roof area in the present study was 7 ha greater, even so, tomato production was not significantly higher in our results, this difference could have occurred because 26.6% of roofs were feasible for open-air systems, and the yield production represents 38% less than that with RTG systems. Concerning other works, quantitative differences were found. In an industrial area of Barcelona, was found that 3% of roofs were feasible while another study carried out in the same city in retail parks showed great potential 53% (Nadal et al., 2017; Sanyé-Mengual, Martinez-Blanco, et al., 2016). The difference about potential roofs could be related to the rooftop building materials, roof systems from retail parks tend to be more resistant than in industrial parks (Sanyé-Mengual et al., 2015a).

In this study, services and housing rooftops were the most feasible for integrating RUA, which can be attributed to the structural requirements. Industrial roofs were present in a larger proportion of the total study area than service roofs. However, a smaller proportion of potential industrial roofs was observed to integrate UA. Generally, this type of roof is characterized by large polygons and a high amount of solar radiation, which makes the integration of RTGs feasible. Even so, most of them have low load-bearing capacity, such as metal decks and light or metal coverings and fiber cement sheets. Low-resistance materials are a barrier to integrating UA systems on roofs in the immediate term, and an adaptation concerning structural reinforcement of the roof is needed for it to be a candidate for UA integration. Similar results were found by Nadal et al. (2017) in an industrial zone of the Metropolitan Area of Barcelona, where roofs met the minimum area and solar radiation but not the load-bearing capacity of the roof material. Service and housing buildings are usually composed of higher load-bearing capacity structures, with non-transitable roof systems composed of concrete and gravel surface finishing or other concrete systems finished with asphalt sheets. These materials meet structural resistance requirements but require a roof finishing adaptation to allow the installation and operation for growing and harvesting food.

Regarding housing buildings, roofs were characterized by a variety of the previous roof systems described, in addition to ceramic roofs, which can fulfill the resistance criterion because concrete systems in general are presented in ceramic roof finishing covers. However, some roofs with too much slope could have metal structures that might not fulfill the resistance requirement. It was noted that the R4 building typology showed greater potential than R5, R2, and R6, which had higher representation over the total study area. These typologies showed many shadows and pronounced slopes, especially the R6 housing typology. Blocks or towers configured from an isolated multifamily building were found to be the most promising typology for RUA purposes. The work developed by Toboso-Chavero et al. (2018) already concluded that block-isolated multifamily buildings have the potential to integrate open-air and RTG systems. These results show that building morphology and urban configuration could play an important role in rooftop UA potential. It was found low percentage (1.5%) of roofs without data information about land use, which could be due to the use of airborne datasets provided by different institutions and acquiring data on different dates which could generate some outdated data.

In the present work, were detected a low proportion of green roofs. As mentioned in Development of the Framework section, green roofs were discarded from the analysis of potential roofs. However, discarding these roofs implies a decrease in the potential of roofs for the integration of food, water, and energy systems, especially, in the case of pioneers cities that support the integration of green roofs and those where green roofs are mandatory by law such as London or Toronto (City of Toronto, 2009; Grant & Gedge, 2019). While green roofs provide environmental benefits, roofs with food, water, and/or energy systems provide several functions that may be a valuable support for developing resilient cities. Productive roofs can contribute to several goals of the 2030 Agenda for Sustainable Development, emphasizing the important role they may play in urban sustainability (Cristiano et al., 2021). Therefore, for future works, it is important to consider the possibility of larger areas of green roofs with the potential for food and solar energy systems integration.

5.4.2 Food, water, and energy self-sufficiency

This work demonstrated food self-sufficiency of 210% (140,620 inhabitants) for tomato consumption. These results are comparable to those reported in previous work by Sanyé-Mengual et al. (2015) in Zona Franca Park (Barcelona) where the total feasible area for RTGs can satisfy the average tomato demand of 130,000 inhabitants. Benis et al. (2017b) determined using a simulation that the integration of RTGs in buildings in Lisbon can have an efficiency of a factor of four in the case of tomato production. However, differences were also found concerning other studies developed in industrial and residential areas of Barcelona, in which self-sufficiency was reported from 50% to 69% (Nadal et al., 2017; Toboso-Chavero et al., 2018). These differences can be attributed to a smaller feasible production area from other works (67% less) in addition witch the use of an extended cycle of 8 months for a tomato crop grew in greenhouse in the present study.

The low feasibility of roofs to integrate lettuce crops in both RTGS (3.6%) and open-air (0.04%) systems is related to the priority given to roofs with high light levels and consequently the consideration of tomato crops, due their consumption in the region is higher than lettuce. However, the roofs that were found to be feasible for tomatoes are also potential for growing lettuce, either year-round or in combined crops with tomatoes (in the months when tomato production is not considered).

With respect to the RWHS for crop production, the results showed that it could be possible to supply at least 63.2% of the water requirements for lettuce crops using both RTGs and open-air and tomatoes growing in open-air systems. The results of this work are better, especially for lettuce growing in open-air systems, which found 94.3% water self-sufficiency compared with that found for a case study in Rome for horticulture gardens, where 57% of water could be supplied by rainwater collection on rooftops (Lupia et al., 2017). These differences can be related to the following reasons: (1) catchment area, this work considered all roof areas as catchment surfaces; (2) RC value, this work considered a variety of RCs (0.9,0.8, and 0.6) according to roof materials in the area, while a conservative value of 0.6 was considered for all potential areas by Lupia et al. (2017); and (3) water requirements, establishment of water consumption for irrigation plays an important role, and soil-less systems, such as perlite, require less water than soil based systems. The water supply by rainwater for growing tomatoes using RTG systems was 27% lower than that in previous experimental works performed in Barcelona, the water efficiency for crops can be improved with the use of leached recirculation, including an extension of the crop production season to obtain 80% of the water requirements for tomato crops (Sanjuan-Delmás et al., 2018) which were no considered in this work. With respect to domestic water self-sufficiency, in this study, it was found that the RWHS could meet up to 44% of household demands. This result is lower to those reported in previous works. According to (Domènech & Saurí, 2011) 60% of the water demand for irrigation and laundry can be meet with the implementation of RWHS in detached and multi-family housing buildings. These differences could be due to the RC values used; previous work considered 0.85 for all roofs (Domènech & Saurí, 2011). The present study incorporates the identification of roofing materials which allowed distinguishing the spatial distribution of them and therefore, considering a variety of RCs from 0.6 to 0.9. Farreny et al. (2013) reported water self-sufficiency ranging from 80% to 90% from water collected from rooftops, in addition to paved covers at ground surface (roads, car park, and paved pedestrian areas) which represented 67% of the catchment area in retail parks from Barcelona. Therefore, considering water harvesting in ground-level areas could increase the potential for water self-sufficiency, however various implications of the system would have to be studied.

Annual and urban-scale irrigation water requirements and rainwater harvesting were calculated in the model. However, a downscaled analysis in temporal terms affects the overall self-sufficiency results (analysis results and their discussion can be found in Supporting information 2.5. Downscaled analysis water self-sufficiency irrigation). In future research, the model can be improved, including analyses at smaller temporal and spatial scales and relate to the size and location of the water tank, which play important roles regarding the feasibility of RWHS and environmental impacts (Angrill et al., 2012b, 2017; Petit-Boix et al., 2018).

Results showed an energy-sufficiency of 18% which is lower than reported in previous studies (ranging from 30% to 46%) from roofs in different districts of Barcelona (Riyahi Alam et al., 2008; Toboso-Chavero et al., 2018). However, differences were found in the data taken as a reference for energy consumption, while this work considered consumption of 11.42 MWh/inhabitant/year (Medi Ambient i Serveis Urbans-Ecologia Urbana Agència d'Energia de Barcelona, 2019), a previous study considered a lower consumption, 2.96 MWh/inhabitant/year (Riyahi Alam et al., 2008).

5.4.3 Solar irradiation and daylight requirements

The use of LiDAR technology made it possible to identify the solar radiation needed for solar energy and food production at a building scale in an urban scale extension. The method used included the meteorological characteristics of the site. Previous works has concluded the need to consider climatic data and field measurements (Kodysh et al., 2013; Suomalainen et al., 2017). However, this work has not made a comparison of the results with other methods used to compute roof radiation. This could be future work. Suomalainen et al. (2017) found an underestimation of the annual solar radiation of approximately 5% on the sunniest spots on the roof compared to solar radiation based on measured. The model of this work considered the shading of vegetation, however, in the case of deciduous vegetation, in winter solar radiation could increase in these areas. From the data obtained with LiDAR and the computation of irradiation for solar energy, a calculator which includes economic indicators could be generated for decision making by stakeholders use.

Most of the rooftops identified as potential for urban agriculture can integrate tomato crops (RTGs and open-air) which require high solar access. A small portion was feasible for lettuce crops, categorized with a medium-light requirement. No potential areas were detected for crops such as microgreens (low light requirement). However, in other locations where solar radiation is low, crops with lower light requirements could be integrated. According to the calculations made in this work, a minimum of 3,800 MJ/m^2/year is necessary for tomato crops in RTGs, which differs from the light requirements (1,900 MJ/m^2/year minimum) used in previous methodologies (Nadal et al., 2017; Sanyé-mengual et al., 2015a; Toboso-Chavero et al., 2018). In future research, the analysis and consideration of intercropping and economic issues are recommended. In addition, to develop new tools using BIM design for modelling and integrate FWE infrastructures on buildings (Benis et al., 2017b; Khan et al., 2018).

5.4.4 Population density building typologies and self-sufficiency

This work considered the characteristics of each building. However, the potential roofs and self-sufficiency at urban scale were analyzed. The population density of each municipality can affect the self-sufficiency potential (for more details of the analysis see Supporting Information 2.6). It is important to note that not all municipalities have the same typologies and uses of buildings. This related to population density has implications at the municipal and building scale in the potential and self-sufficiency. For example, service and residential buildings showed higher potential for urban agriculture compared to industrial buildings. In the municipality with the lowest population density was found the largest amount of service building area. In this municipality, is located the Autonomous University of Barcelona representing the largest area of educational services. Contrary, most of the building housing with potential are in the county with the highest population density.

Concerning the integration of two systems: photovoltaic and rainwater harvesting, industrial roofs were found more feasible. Seventy-six percent of the potential industrial area was identified in the municipality of Barbera del Valles, while in the most densely populated municipality, there was no industrial buildings. Therefore, in future research, it is recommended to include analysis on a smaller scale, considering the variables mentioned in the previous paragraph.

5.4.5 Other considerations for future works

The conflict of prioritizing a roof use solar energy generation vs food production could be solved with the emergence of new technologies such as TPV integrated into RTGs. These new types of panels will allow the coexistence of both energy generation and food production. However, although TPV has been extensively researched as a renewable energy source for urban areas, there are still several challenges that do not seem to be fully covered yet. For commercialization of the TPV some main perspectives should be considered high-power conversion efficiency at the same average visible transmittance, aesthetic factors, and feasibility for real-world applications, including modularization and stability evaluation. In this regard, it has been suggested that a high-performance TPV cannot be realized commercially yet (K. Lee et al., 2020). However, in future research, it is recommended to integrate them in methodologies for feasibility and self-sufficiency analysis considering both food and solar energy systems in the same infrastructure.

According to Toboso-Chavero et al. (2018) the combinations with larger CO_2 eq savings showed higher self- sufficiency in electricity and hot water, whereas the combinations with lower environmental impacts displayed higher self-sufficiency in food systems. Benis et al. (2018b) found that food production is more beneficial than energy production for both financial return and local job creation. These important environmental and economic impacts must be considered in future studies.

5.5 Conclusions

This study contributes to defining criteria and procedures for assessing the feasibility of rooftops for integrating urban agriculture, rainwater harvesting systems, and PV panels. The framework developed in this work demonstrated an automatic, potential, and efficient tool to identify potential roof areas. It is still important to carry out site visits to the buildings to which the infrastructure is to be integrated to verify the roof materials, structural design, and load-bearing capacity. Data acquisition from remote sensing technology is the basis of the defined framework. In this sense, the availability of data is important. The identification of roof materials can be estimated through the proposed method and the use of remote sensors in the present study. The lack of this information could be a limitation for determining the potential adequate load capacity for the installation of greenhouses and could constitute an information gap in evaluating the potential integration and self-sufficiency of FWE systems in different cities. A lack of information concerning the consumption of products and production at the local or regional level could restrict or lead to less accurate production and self-sufficiency analyses. In relation to this limitation, experimental research on rooftop agriculture for both RTGs and open-air systems in different regions and considering a diversity of crops and according to their consumption products is needed.

In Mediterranean and other regions where high radiation potential is available, daylight should be taken as advantage for crops with high lighting requirements without use of artificial light support.

Urban morphology and its characteristics influence the feasibility of potential production, especially for food and energy. Thus, the relationship between urban morphology and building typologies regarding FWE systems must be performed more deeply. This issue could be addressed by characterizing urban structure types using remote sensing technology due to the potential for efficient derivation of mapping urban land at the city scale.

The results of this work indicate that housing and services buildings could be a better location for RUA than industrial buildings. In addition, RUA could represent social cohesion and educational values more directly. However, in other cities building typologies and uses with the greatest potential may be different.

Regarding water self-sufficiency for crop production, the case study demonstrated good performance for most of the systems studied. However, this performance is variable according to the rainwater amounts of the case study location. Some implications can be improved for future works, for example, considering the recirculation of leachate and the factor of occupied area by crops in the case of open-air systems, as well as with respect to water tanks, size calculations, and feasibility locations, which could be restrictions for implementing RWHS regarding the tank weight and associated environmental impacts.

It is critical to include social, environmental, and economic indicators to carry out a complete sustainability assessment and to guarantee economic sustainability of the infrastructures.

It is important that information about potential roofs be accessible and easy to identify. In this regard, an interactive map with the location and information of these areas has already been implemented in some cities, for example, the rooftop project maps of Melbourne city (City of Melbourne, 2020). Developing this type of interactive map could represent a valuable contribution to decision making for planning.

This work explored potential rooftops already built, but the integration of FWE systems into new buildings is also important. The expansion of cities continues, and the nexus of FWE systems should be considered a part of new buildings. In this sense, the integration of water and energy flows as well as UA in the phase of project design is an important consideration and easier to integrate if the project is conceived from the beginning with the integration of these technologies in mind. For these reasons, it is crucial that FWE studies also focus on the development of new projects and designs that will strongly depend on the geographic location.

Part IV

Social scale.
Potential barriers and opportunities for integrating urban agriculture on roofs

Chapter 6

Potential key factors, policies, and barriers for rooftop agriculture in EU cities: Barcelona, Berlin, Bologna and Paris

CHAPTER 6 - Potential key factors, policies, and barriers for rooftop agriculture in EU cities: Barcelona, Berlin, Bologna and Paris

This chapter is based on the following journal paper[4]:

Zambrano-Prado, P; Orsini, F; Rieradevall, J; Josa, A & Gabarrell, X (2021) Potential Key Factors, Policies, and Barriers for Rooftop Agriculture in EU Cities: Barcelona, Berlin, Bologna, and Paris. Frontiers, Sustainable Food Systems, 5:733040. https://doi.org/10.3389/fsufs.2021.733040

Abstract

The main objective of this study is to contribute a framework and to provide an overview of potential key factors, policies, and barriers associated with the integration of rooftop urban agriculture (RUA), building on stakeholders' perspectives in four European cities (Barcelona, Berlin, Bologna, and Paris). The research was developed in two phases, namely, a workshop and a survey using a Likert scale and applied to stakeholders involved in RUA from the four cities. Education, environmental, research, technological innovation, food production, and social factors play an important role in implementing RUA. Productive spaces, cultural values, social cohesion, social rural-urban links, and the high cost of urban land are highlighted as factors that "promote" RUA. In contrast, the cost of water and pollution are major contextual factors that constrain RUA. Policies related to food trade and urban planning are those that most limit RUA development. Major architectural and technical barriers related to the limits on building heights, historical buildings, a lack of specific building codes, building design and roof accessibility were identified. The high cost of infrastructure and policies that prohibit RUA product sales emerged as economic constraints. Major differences among the cities studied included the perceived effect of urban policies on RUA diffusion as well as the perceived relevance of economic and pollution factors. This study revealed that extensive dissemination and the development of appropriate information about RUA are needed. The creation of new regulations, as well as modifications to urban and building codes to support RUA, is also envisaged. This approach will consider a more flexible land-use policy that allows agriculture to take place in cities as well as marketing frameworks for RUA products. For future studies, it would be useful to apply the framework developed in this study to a larger sample. A study is also needed to confirm hypothetical differences between cities.

Keywords

Urban agriculture, stakeholders' perceptions, policies, sustainability

[4] Journal proofs status when this thesis was finished

6.1 Introduction

In recent decades, the world population has undergone revolutionary changes. Population dynamics have resulted in the rapid growth of the global population since 1950. Today, 55% of the world's population lives in urban areas, and according to projections, by 2050, 68% of the world's population is expected to live in cities (United Nations, 2018a). Cities, as spaces where human activity is more concentrated, must develop a key role in the management of the present and future of humankind and the development of a more sustainable organizational model (European Commission & United Nations Human Settlements Programme, 2016).

Land and water systems face the risk of a progressive collapse of their productive capacity under a combination of demographic pressure and unsustainable agricultural practices. Intensive forms of agriculture can cause serious environmental damage, with food crops also competing for land, water, and energy resources (Bilan et al., 2018). Factors such as rapid urban growth, scarce resources, and the effects of climate change contribute to highly vulnerable food systems (FAO, 2011; Martellozzo et al., 2014). The COVID-19 pandemic has underlined the need for modifications and changes in the governance of food systems. To address food resilience, it has been suggested that European governments promote local production involving innovative small-scale initiatives, whose social benefits have been emphasized by the pandemic (Vittuari et al., 2021). Indeed, the integration of food production within cities may offer opportunities to address these challenges (Armanda et al., 2019).

Cities, especially those with a high population density, lack sufficient space for agricultural uses. In this sense, real estate speculation and the increase in population density in urban areas have led to a decrease in the availability of vacant lands where urban agriculture (UA) may be developed (Gasperi et al., 2016). Thus, given the multiple benefits in terms of social, economic, and environmental functions provided by UA and the growing interest in the creation of sustainable cities with improved quality of life, city farming, made up of a diversified set of growing systems and business strategies (Orsini et al., 2020), is being widely promoted (Taylor & Hochuli, 2017). Among possible strategies for fostering urban food production, vacant building rooftops have been proposed as locations where the transformation from underused to productive spaces may take place (Orsini et al., 2014; Toboso-Chavero et al., 2018).

6.1.1 Urban agriculture benefits and barriers

In recent years, a growing number of UA projects have been established on existing buildings, for example, using façades and rooftops as crop production space (Thomaier et al., 2015). Rooftop urban agriculture (RUA) can play an important role in improving adaptation to climate change (De Zeeuw et al., 2011), can reduce the urban heat island effect (Alexandri & Jones, 2008; J. S. Lee et al., 2014; Susca et al., 2011), and may ultimately lower energy and greenhouse gas emissions by decreasing the distance that food products are transported (Heinberg & Bomford, 2009). Other benefits are also associated with the integration of disadvantaged population groups and the promotion of social cohesion (Draper & Freedman, 2010; Lovell, 2010), while also providing economic benefits within communities. However, even in the face of such benefits, several concerns must be addressed for the successful integration of UA in cities (Fletcher et al., 2012), with urban planning and economic, social, and environmental issues representing the main challenges. Policies, regulations, and land-use zoning bylaws can also act as barriers to UA (Roehr & Kunigk, 2009). Until recently, many municipalities excluded agriculture or related activities within their regulations for residential land use. For instance, until June 2010, the City of Los Angeles (California, USA) prohibited residents from growing crops in residential-zoned areas. (Fletcher et al., 2012). Restriction on sales of food products grown in residential areas is also a barrier and major concern, although exceptions exist. In 2012, the Berkeley Planning Commission adopted the definition of "Non-Processed Edibles", which includes locally produced fruit, vegetables, nuts, honey, and shell eggs, but not meat, allowing the sale of such items in residential districts, provided that they meet certain safety requirements (Fletcher et al., 2012). Other cities were also highly active in implementing policies to support UA, including New York City, Washington DC, Chicago, Toronto and Singapore, where pioneering programs related to food production on building rooftops were launched. The New York City council also included the use of rooftops for food production in local plans (The New York City Council, 2010). Additionally, the city of Chicago reformed city laws regarding UA, allowing urban farms on rooftops (City of Chicago, 2020; Urban sustainability exchange, 2011). Globally, North America (81) and Europe (49) are the world regions with the highest number of RUA projects (Appolloni et al., 2021).

6.1.2 Rooftop urban agriculture integration in European cities

In Europe, the lack of land has led to exploring new ways to promote horticulture in cities, with pioneering practices of RUA taking place, for example, in Barcelona, Berlin, Bologna, and Paris.

In Barcelona (Spain), a pilot rooftop greenhouse (RTG) started to operate in the ICTA-ICP building of the Universitat Autonòma de Barcelona in 2014 (Fertilecity, 2018). Other local examples of RUA include the L'Hort al terrat (Garden on the roof) program, promoted by the City Council and aimed at fostering the integrated production of different kinds of vegetables (Barcelona City Council, 2018b). Additionally, the recently released Barcelona's Climate Plan 2018-2030 considers RUA implementation as a means to mitigate climate change and improve the quality of life in the city (Barcelona City Council, 2018a). Barcelona will also host the international meeting of the Milan Pact, becoming the World Capital of Sustainable Food in 2021 (Barcelona City Council, 2020).

In Berlin (Germany), commercial urban farming enterprises have developed different prototypes and technologies for food production on buildings (Specht et al., 2016c). The high potential for integrating RUA was recently detailed (Altmann et al., 2018), and RUA projects are already operative, including two open-air rooftop gardens and one RTG, located on the Humboldt University building (Tao et al., 2020).

Bologna (Italy) was one of the first cities in Italy to adopt a local plan for adaptation to climate change. Greening strategies were proposed to mitigate the effects of urban heat islands, with the ambitious objectives of integrating 5 hectares of urban vegetable gardens and greening intervention on ten public buildings (Comune di Bologna, 2014). Although the actual development was on a smaller scale (e.g., three temporary pilot community rooftop gardens installed on the 10th floor of social housing buildings, Orsini et al., 2014), new RUA projects are currently being developed, including an educational rooftop greenhouse at the multifunctional space SALUS (Pennisi et al., 2020).

Paris (France) has been very active in promoting projects concerning biodiversity, greening, UA and food initiatives (Delgado, 2018). According to the Paris Climate Action Plan, the city promotes UA on roofs of municipal buildings. One of the objectives is to install 100 hectares of green roofs and walls, one-third of which will be devoted to urban agriculture (City of Paris, 2018). Accordingly, the Parisculteurs program was launched in 2016 for installing urban agriculture on buildings (Collé et al., 2018).

While the RUA sector is growing steadily in different European cities, economic, social, environmental, legal, technical, and architectural limitations are also being identified, as will be detailed in the following section.

6.1.3 Rooftop urban agriculture barriers in European cities

Although pioneering RUA projects exist, most suffer from a lack of promotion, specific laws, legal procedures, and urban codes (Cerón-Palma et al., 2012; Sanyé-Mengual et al., 2013). Studies in Barcelona, Berlin, and Bologna developed a preliminary classification of such barriers (Cerón-Palma et al., 2012; Sanyé-Mengual et al., 2016; Specht et al., 2015; Specht et al., 2016a; Specht & Sanyé-Mengual, 2017). Social obstacles include limited acceptance by users, the conceptualization and perception of UA, by many stakeholders, that it is not "true" agriculture, and the urgent need for training qualified technical personnel (Sanyé-Mengual et al., 2016; Specht et al., 2016a; Specht & Sanyé-Mengual, 2017). Social and health risks have also been repeatedly identified in several surveys on citizen perceptions (Sanyé-Mengual et al., 2016; Sanyé-Mengual et al., 2018b; Specht & Sanyé-Mengual, 2017). Additionally, the possible environmental impacts associated with materials used for the construction of RTG facilities require careful consideration (Cerón-Palma et al., 2012). The low level of income generated by RUA products and difficulties in developing a viable business model were found to be the principal economic concerns (A. Palmer et al., 2016; Specht & Sanyé-Mengual, 2017). Technological and architectural barriers included the visual/aesthetic impact (especially within historical centers), structural load limitations in buildings, building height limits according to the building size, and the overall building envelope (Cerón-Palma et al., 2012; Sanyé-Mengual et al., 2016; Specht et al., 2016a). Legal challenges range from the lack of RUA regulations in current urban building codes and the difficulties in managing food safety protocols and certification schemes within small-scale farms. While the few studies that have been conducted have identified the barriers, opportunities, and risks associated with urban agriculture, there is a gap in identifying specific policies and key factors that can contribute to or limit urban agriculture on rooftops.

6.1.4 Approaches for identifying rooftop urban agriculture barriers and opportunities

Table 1 presents studies conducted to identify barriers and opportunities for implementing RUA in European cities from the point of view of stakeholders or citizens.

Table 6.1. Studies of barriers and opportunities from stakeholders' perceptions

City	System	Data collection			Key approach	Related approach				Reference
		I	S	Q		K	R	C	S	
Barcelona	RTGs		●		Barriers and opportunities					(Cerón-Palma et al., 2012)
Berlin	ZFarming	●			Opportunities and challenges	●				(Specht et al., 2015)
Barcelona	URF	●			Barriers and opportunities			●		(Sanyé-Mengual et al., 2016)
Berlin	ZFarming	●			Benefits and risks		●			(Specht et al., 2016a)
Berlin and Barcelona	URF	●			Risks		●			(Specht & Sanyé-Mengual, 2017)
Bologna	UA*			●	Social acceptance				●	(Sanyé-Mengual, Specht, et al., 2018)
Germany and U.S.	UFP	●			Perception of sustainability, acceptance factors and acceptance barriers					(Specht et al., 2019)

Data collection was performed using interviews (I), seminars of discussion (S), and questionnaires (Q). Related approaches: key factors (K), relevance (R) of benefits and risks, comparison with previous studies on RUA (C), and scale of acceptance (S).

As revealed in Table 1, Barcelona and Berlin are the cities where the greatest number of studies have been conducted. Interviews are the most frequent method used for data collection (Sanyé-Mengual et al., 2016; Specht et al., 2015; Specht et al., 2016; Specht & Sanyé-Mengual, 2017). Most of the key approaches are related to barriers, opportunities and risk. Regarding related approaches, two studies identified the level of relevance of benefits and risks (Specht et al., 2016; Specht & Sanyé-Mengual, 2017), one study identified key issues for implementing UA (Specht et al., 2015), another compared its results on RUA with findings of previous studies (Sanyé-Mengual, Anguelovski, et al., 2016), and finally, one study used a Likert-scale evaluation to identify the degree of social acceptance of uses of open and green spaces, including RTGs and rooftop farms in the city of Bologna (Sanyé-Mengual, Anguelovski, et al., 2016).

Studies that consider data collection methods where stakeholders interact and share their knowledge and experiences to address barriers, opportunities, key factors, and policies regarding the implementation of RUA projects, as well as quantitative approaches about the frequency and degree of relevance of such projects, are also lacking. RUA is advancing driven by local initiatives. This gives rise to diverse models that correspond both to the circumstances of each location and to the restrictions (or support) that exist in each case. There is, therefore, a crucial need to identify the key factors, policies, and barriers associated with the implementation of RUA in cities, especially when there are recent experiences. The identification of these little-explored aspects is relevant and helpful to find common factors, collect constraints, ways to overcome them and propose lines of action, this could help in the development of policies and programs to promote urban agriculture more efficiently and overcome constraints. These actions could bring various social, educational, environmental, and economic benefits in the urban context, as well as contribute to building more resilient cities.

The present study includes four cities from different European regions where incentives to support RUA have recently emerged and projects have already been built with different focuses, ranging from social inclusion to technological development and research. This study primarily elaborates on a participatory workshop. Participatory workshops are processes by which communities of practitioners can collaboratively share knowledge and personal experiences and reflect on the challenges they face and the methods for addressing them (Mor et al., 2012). Research methodology workshops aim to produce reliable and valid data about the domain in question and regarding forward-oriented processes in addition to fulfilling participants' expectations to achieve something related to their own interests (Ørngreen & Levinsen, 2017). The workshop cocreates a space for negotiating collaborative meanings, not just between participants but also between researchers and participants who discuss, perform, and learn during the workshop (Ørngreen & Levinsen, 2017).

In this context, the main objective of this research is to provide an exploratory overview of potential key factors, policies, and barriers associated with the integration of RUA from stakeholders' perceptions in four European cities (Barcelona, Berlin, Bologna, and Paris). The specific objectives of this work are (1) to identify key factors for integrating RUA and their level of relevance, (2) to identify context factors and their perceived effect on RUA diffusion, (3) to identify policies and their perceived effect on RUA diffusion and (4) to identify barriers to RUA and the frequency with which they occur.

6.2 Materials and Methods

An exploratory method and nonprobability sampling were used. The results are therefore not to be considered statistically or demographically representative of stakeholders from Barcelona, Berlin, Bologna, and Paris. The exploratory approach was considered appropriate because it offers preliminary insights into a previously little or unexplored topic (Hernández-Sampieri, 2014).

Figure 6.1 shows the workflow, structured in two phases and seven stages. The first phase consisted of a workshop. The main goal of the workshop was to obtain an overview of key factors, contextual factors, policies, and barriers to RUA integration in cities based on stakeholders' experiences. The second phase aimed at identifying, and quantifying, stakeholders' perceptions about key factors relevant to integrating RUA, contextual factors and policies that promote or hinder RUA, and the frequency with which barriers occur. Within Phase 1, the research included a definition of the case studies (stage 1), the participant definition (stage 2), and data collection (stage 3). Phase 2 included key factor and barrier definitions (stage 4), a second round of participant definitions (stage 5), data collection (stage 6), and analysis (stage 7). Each of these stages is described in detail in the following subsections.

Figure 6.1. Workflow for identifying key relevant factors that hinder and promote policies and barriers in RUA projects based on stakeholder perceptions in four European cities.

6.2.1 Phase 1 Workshop

The first phase consisted of a workshop with international stakeholders from diverse EU cities. A participatory workshop was developed to build knowledge concerning to RUA.

Definition of case studies

Four cities from Europe, Barcelona, Berlin, Bologna, and Paris were chosen as case studies, given that they recently hosted some highly innovative RUA projects aimed at social inclusion, technological development and research. Among them, policies for supporting RUA have been implemented only in Paris (Paris City Council, 2018), whereas in other cities, existing regulations do not specifically target these kinds of projects (Cerón-Palma et al., 2012; Freisinger et al., 2015; Orsini et al., 2014). Table 6.2 shows a summary of the main characteristics of the case studies. Barcelona is a compact Mediterranean city (Parés et al., 2013; Rueda, 2007). It has 1.6 million inhabitants in 101 km^2 and features a population density of 16,420 inhabitants/km^2 (Statistical Institure of Catalonia, 2020), being among the densest and most compact municipalities in Europe (Barcelona City Council, 2018). The lack of land has led to exploring new ways to promote horticulture in the city, such as the RTG located on the ICTA-ICP building with a focus on research for technology innovation (Fertilecity, 2018). The city of Berlin has 3.7 million inhabitants (Berlin business location center, 2019) who live over a surface of 892 km^2 (OECD, 2010) with a population density of approximately 4,147 inhabitants/km^2 (Environmental atlas Berlin, 2018). Today, among existing RUA projects, two rooftop gardens have a particularly social focus, whereas an RTG for applied research in botany and plant biology can be found at the Humboldt University building. Bologna is the main city of the Emilia Romagna Region, situated in northcentral Italy, and with a population of 394,463 inhabitants in 140.7 km^2, resulting in a population density of 2,738 inhabitants/km^2 (ISTAT, 2010, 2021). Paris has 2.2 million inhabitants living on a surface area of 105 km^2. This results in one of the highest urban densities in the world, reaching values in inner Paris of 20,755 inhabitants per km^2 (INSEE, 2017). The City Council was recently very active in promoting projects targeting biodiversity preservation, greening, UA and food initiatives (Delgado, 2018). In 2016 and 2017, the first and second editions of the Parisculteurs program were launched, creating social inclusion and research spaces (Collé et al., 2018).

Table 6.2. Summary of cases studies

City	Inhabitants (million)	Population density (inhabitants/km^2)	Rooftop urban agriculture projects		
			Technological development	*Research*	*Social inclusion*
Barcelona	1.6	16,420	●	●	●
Berlin	3.7	4,147		●	●
Bologna	0.4	2,802			●
Paris	2.2	20, 755		●	●

Participants' definition

The second stage of the research consisted of the identification and classification of the UA experts to be involved. This included UA project developers (e.g., architects, agronomists), public administrators (with responsibilities in assigning municipal licenses and developing urban planning strategies), academics and researchers, and citizens involved in UA initiatives. Furthermore, relevant stakeholders from the cities of Barcelona, Berlin, Bologna, and Paris were identified and invited to define the state of the art of RUA in their cities.

Data collection

To collect data from stakeholders, a workshop (Cerón-Palma et al., 2012) was conducted at the ICTA-ICP building (located in Barcelona) in September 2017. During the workshop session, interventions were recorded by the workshop organizers. The five stages developed in the workshop for data collection are described below.

1) Problem and context. The workshop began with an introduction about the problem and context of RUA panorama. This part of the workshop was presented by a member of the project team who is a lawyer specialising in environmental issues. As a second step of this phase, international speakers were presented.

2) Sharing expertise. International experiences from Barcelona, Berlin, Bologna, and Paris were shared. The presentations set the context of key factors, policies, and barriers for integrating RUA, problems in the target domain, also RUA projects already built or in the project phase were presented. Experiences were shared by specialists on UA: from Barcelona, the Technical Director of the Municipal Institute of Urban Landscape from the Barcelona City Council; in the case of Italy, a researcher from the Center in Urban Environment for Agriculture and Biodiversity from Bologna University; from Paris, a member of Agroparistech; and in the case of Berlin, a master's student enrolled in the Interdisciplinary Studies in Environmental, Economic and Social Sustainability program from the UAB.

3) Collaborative reflections. A discussion session was held among the participants. The participants were asked to reflect and share experiences and perceptions about the following questions:

   Which are the key factors for integrating RUA?
   Which are the policies that promote RUA?
   Which are the barriers for integrating RUA?

4) Extraction of common and different features. Similar key factors, policies and barriers from stages 2 and 3 were grouped together.

5) Sharing of results. Findings from the workshop were presented by the moderator of the session to all participants and final debate on the results obtained was developed.

6.2.2 Phase 2 Survey

The research then evolved into a survey, integrating results from phase 1 (workshop) with a comprehensive literature review. This phase comprised the four steps described below.

Key factors and barriers definition

Six main categories were identified, namely, urban, environmental, social, legal, technological/architectural, and economic barriers and opportunities (Cerón-Palma et al., 2012; Nadal, Oriol, et al., 2018; Sanyé-Mengual et al., 2016; Specht & Sanyé-Mengual, 2017).

Participants' definition

Experts involved in UA, including project developers, public administration, academics, and citizen initiatives from Barcelona, Berlin, Bologna, and Paris, were identified and invited to participate in the survey.

Data collection

Data collection was carried out from November to December 2017. The survey was designed to evaluate stakeholder perceptions through Likert scales that provided a range of responses to a series of statements. Five categories of responses were included (Croasmun & Ostrom, 2011), ranging from 5 to 1. The survey was structured into six sections: (1) survey description and context, (2) stakeholder information, (3) key issues for integrating RUA, (4) factors that hinder or promote RUA, (5) public policies to promote RUA, and (6) barriers to integrating RUA. Participants indicated their degree of agreement with a specific statement regarding the environmental, urban, social, legal, technological, architectural, and economic dimensions. Survey sections are further described in Supporting information 3.1. Description of survey sections

Data analysis

A quantitative analysis of the survey results was performed, enabling us to define local and global trends in the responses and overall perceptions of the stakeholders.

6.3 Results

6.3.1 Phase 1 Workshop

The workshop was attended by 34 stakeholders, grouped by project developers (3), public administrators (6), academics (23), and those involved in citizen initiatives (2).

International experiences of urban agriculture: Berlin, Bologna, Paris, and Barcelona

Figure 6.2 shows a summary of the results (see complete data in Supporting information 3.2. Complete international experience workshop results). Increased biodiversity, generation of green spaces, educational research and social purposes, environmental CO_2 reduction, building energy optimization, new business generation, and new technology development were identified as potential key factors for integrating RUA. Urban planning, building laws, tax reduction, subsides, educational policies, and local policies, e.g., the Paris Climate Action Plan, Parisculteurs, and Plan Local d'Urbanisme de Paris (Paris Local Urban Plan) from Paris and the Primer Concurs de Cobertes Verdes (First Green Roof Contest) from Barcelona, were identified as policies that potentially "promote" and are related to RUA. Potential barriers identified included legal gaps, lack of a specific legal framework, building codes, administrative processes, restrictions on food sales, urban codes, health risks, historical building codes, rooftop accessibility difficulties, building designs, building structural features (overloading), high costs of infrastructure, climatic conditions, residents opposed to agricultural roofs on their buildings, lack of economic benefits, cost of water, firemen codes, food-free distribution, economic crisis, and a lack of interest by society.

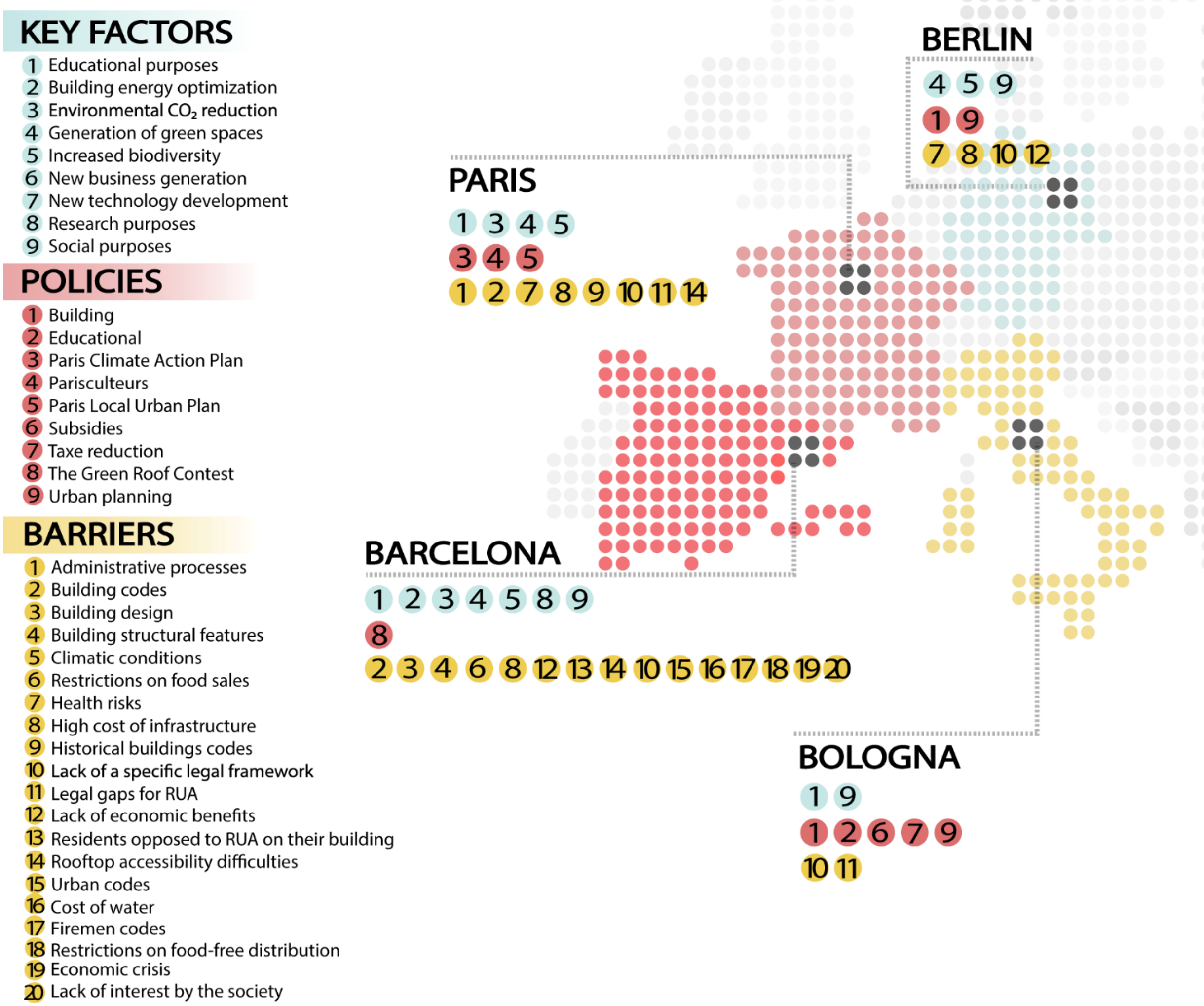

Figure 6.2. Key factors, policies and barriers regarding RUA projects according to stakeholder perceptions in four European cities.

6.3.2 Phase 2 Survey

Survey to identify potential key RUA factors and barriers

Thirty stakeholders responded to the survey Figure 6.3 shows the distribution of participants and their field of expertise regarding UA, made up of 5 participants from Barcelona, 7 from Bologna, 6 from Berlin, and 12 from Paris. Fifty percent of the respondents were academics and researchers, 40% of stakeholders were project developers, and 10% were public administrators.

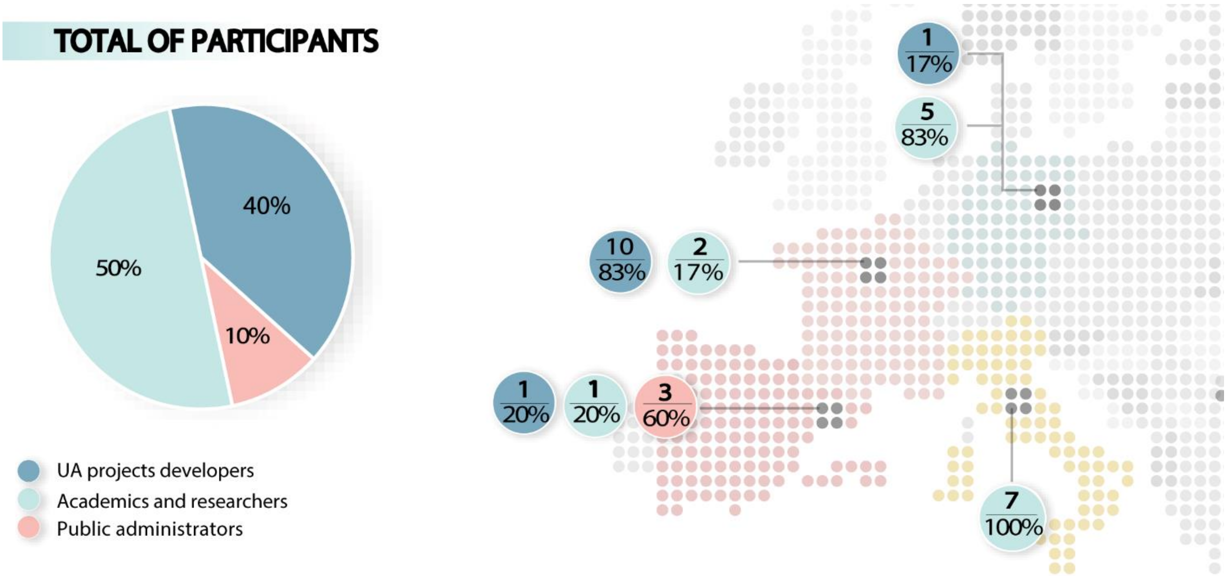

Figure 6.3. RUA survey participants and their sectors.

Potential key factors for integrating RUA

Figure 6.4 summarizes the key factors identified by more than 50% of participants (see all information in Supporting information 3.3. Perceived relevance of key factors for integrating RUA). Two factors—*educational* and *environmental*—were unanimously perceived as "relevant" by participants from Barcelona and Berlin. *Educational* factors refer to the integration of RUA as a tool for developing educational activities. *Environmental* factors include functions such as increasing biodiversity, generating green areas, reducing CO_2, and mitigating urban heat islands. *Research* from a multidisciplinary approach, including agriculture, environmental sciences, urban planning, architecture and social sciences, *technological innovation* related to new forms of UA, *food production* within city limits, and *social* functions are key factors perceived as "relevant" for integrating RUA.

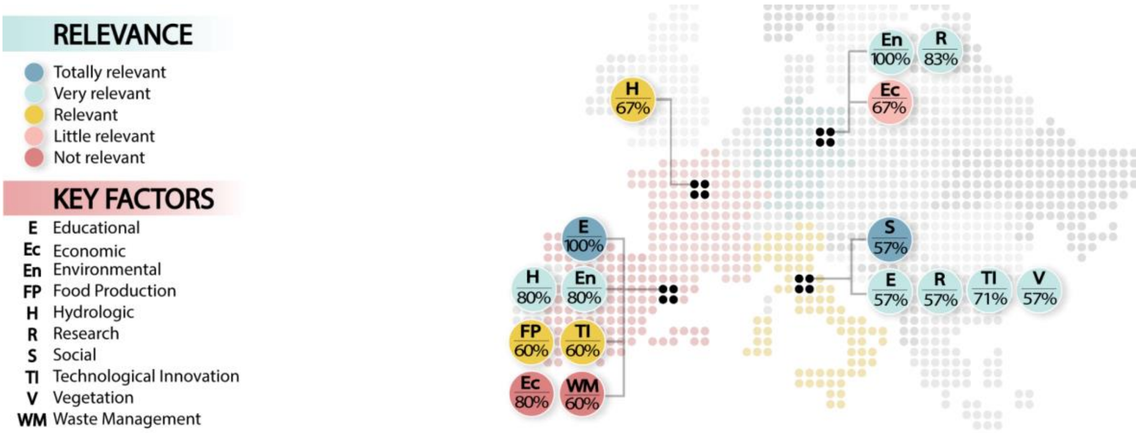

Figure 6.4. Perceived relevance of key factors in four European cities for integrating RUA.

Context factors and their perceived effects on RUA diffusion

Figure 6.5 summarizes the contextual factors and global and local trends that hinder or promote RUA that were identified by more than 50% of the stakeholders (see all information in Supporting information 3.4. Context factors and perceived effect on RUA diffusion). Globally, *pollution* was the only factor identified as a condition that "hinders" RUA. Those factors that "promote" RUA with the highest agreement (66%) among stakeholders were *cultural values* and *social rural-urban links*. Local trends showed five context factors perceived as "promoting" RUA: *productive spaces*, *cultural values*, *social cohesion*, *social rural-urban links*, and the *high cost of urban land*. The *cost of water* was perceived as a "hindering" factor to a similar degree both in Barcelona (75%) and Bologna (71%). There was some disagreement on the *pollution* factor; participants from Bologna (71%) identified it as a "promoting" factor, while participants from Barcelona and more than half from Paris (71%) identified it as a "hindering" factor.

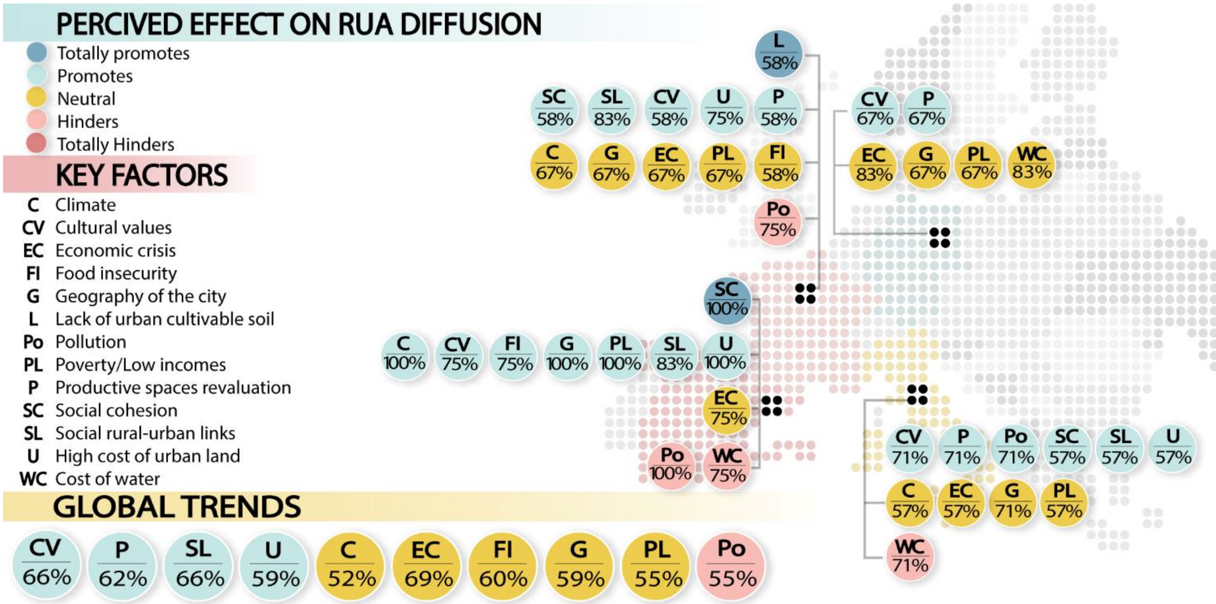

Figure 6.5. Context factors and perceived effect on RUA diffusion in four European cities.

Policies and their perceived effects on RUA diffusion

Figure 6.6 presents a summary of policies selected by more than 50% of participants, both globally and by city (see all information in Supporting information 3.5. Policies and their perceived effect on RUA diffusion in four European cities). Five policies were identified in the target cities as "promoting" RUA. The *sustainability policy* obtained greater agreement (79%) among participants from all cities, followed by the *Milan Food Policy Pact* (62%). According to local trends, six policies were identified as "promoting" RUA. One was found to be common in all cities: policies targeting *sustainability*. The remaining five policies targeting *financial incentives*, the *development of new technologies*, *education*, and *food production*, as well as the *Milan urban food policy pact* and the *Parisculteurs* program, were identified as "promoting" RUA. Policies related to *food trade* were considered to "hinder" RUA by all the participants from Barcelona and, to a lesser extent, by the participants from Paris. Policies related to *urban planning* were perceived by participants from Barcelona and Paris as "hindering" RUA and by those from Bologna as a "promoting" factor, while those from Berlin were "neutral".

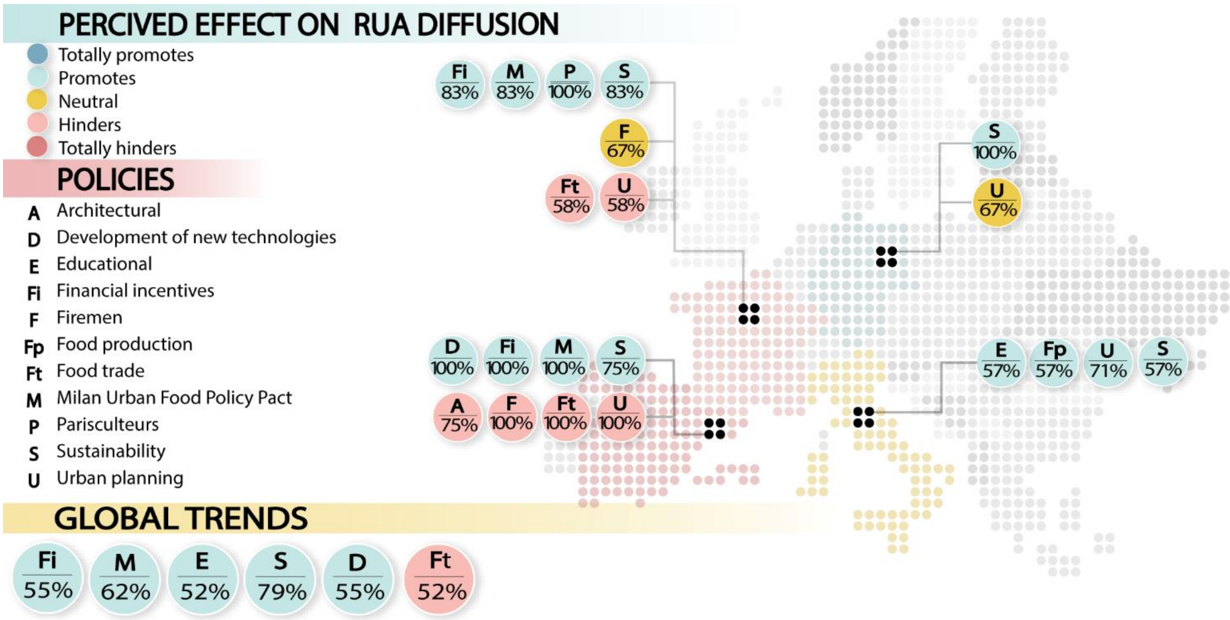

Figure 6.6. Policies and perceived effect on RUA diffusion in four European cities.

6.3.3 Barriers for integrating RUA

Figure 6.7 summarizes the barriers, and the frequency of their presence, to integrating RUA, both globally and by city. Only those barriers identified by more than 50% of participants are shown (see all information in Supporting information 3.6. Barriers and the frequency with which they occur in four European cities RUA). The following section presents the barriers by category.

Architectural barriers

There was no common architectural barrier for any of the cities studied. Three barriers were identified by stakeholders from Barcelona as factors that "always" and "almost always" hinder RUA: *prohibition in historical buildings*, *building codes that do not consider RUA* and *building height*. On the other hand, four architectural barriers were perceived as "rarely" or "never" hindering RUA by participants from Barcelona and Berlin: that *RUA is prohibited in all new buildings*, *RUA is prohibited in existing buildings*, *RUA is allowed with restrictions on the materials used*, and *building codes that prohibited RUA due to sightline visibility* (from the rooftop to other building).

Technical barriers

As was the case with architectural barriers, no common technical barrier was found in any of the cities. *Building design hinders logistics to operate RUA* and *building design hinders roof accessibility* were identified as "almost always" occurring by stakeholders from Berlin and Barcelona. *Sloping rooftop hinder RUA* was identified as "rarely" appearing by stakeholders from Barcelona. *Competition for the use of roofs* was identified by Paris (67%) and Bologna (57%) stakeholders as a barrier that "*sometimes*" appears and by participants from Barcelona (60%) as only "*rarely*" appearing.

Economic barriers

The results showed that there was no economic barrier found by all cities; however, the *high cost of infrastructure* was reported as a barrier that is "almost always" present by participants from Barcelona (80%) and Paris (58%). *Policies that prohibit food sales* were reported by participants from Barcelona as a barrier that "almost always" occurs. In addition, Barcelona was the only city that identified barriers as "*always*" present—*policies that prohibit the free distribution of food*— and "rarely" present—the *lack of legislation for sales of food harvested on rooftops*.

Social barriers

As in previous barrier categories, no common social barrier was found in the target cities. In this group, *exclusive access to rooftop food and projects* and *lack of interest by society* were identified as social barriers that are "rarely" present; the presence of *residents who do not want rooftop agriculture in their building* was identified by respondents from Barcelona as a barrier that "sometimes" appears.

Urban planning

Again, in this category, no common barrier was found among all cities. However, the results showed that the *lack of a legal framework for agricultural land use in the city* was identified by stakeholders from Barcelona and Berlin as "almost always" and "sometimes" present, respectively. An *urban planning zoning ordinance that prohibits agricultural land use in the city* was perceived as "almost always" an issue by stakeholders from Barcelona.

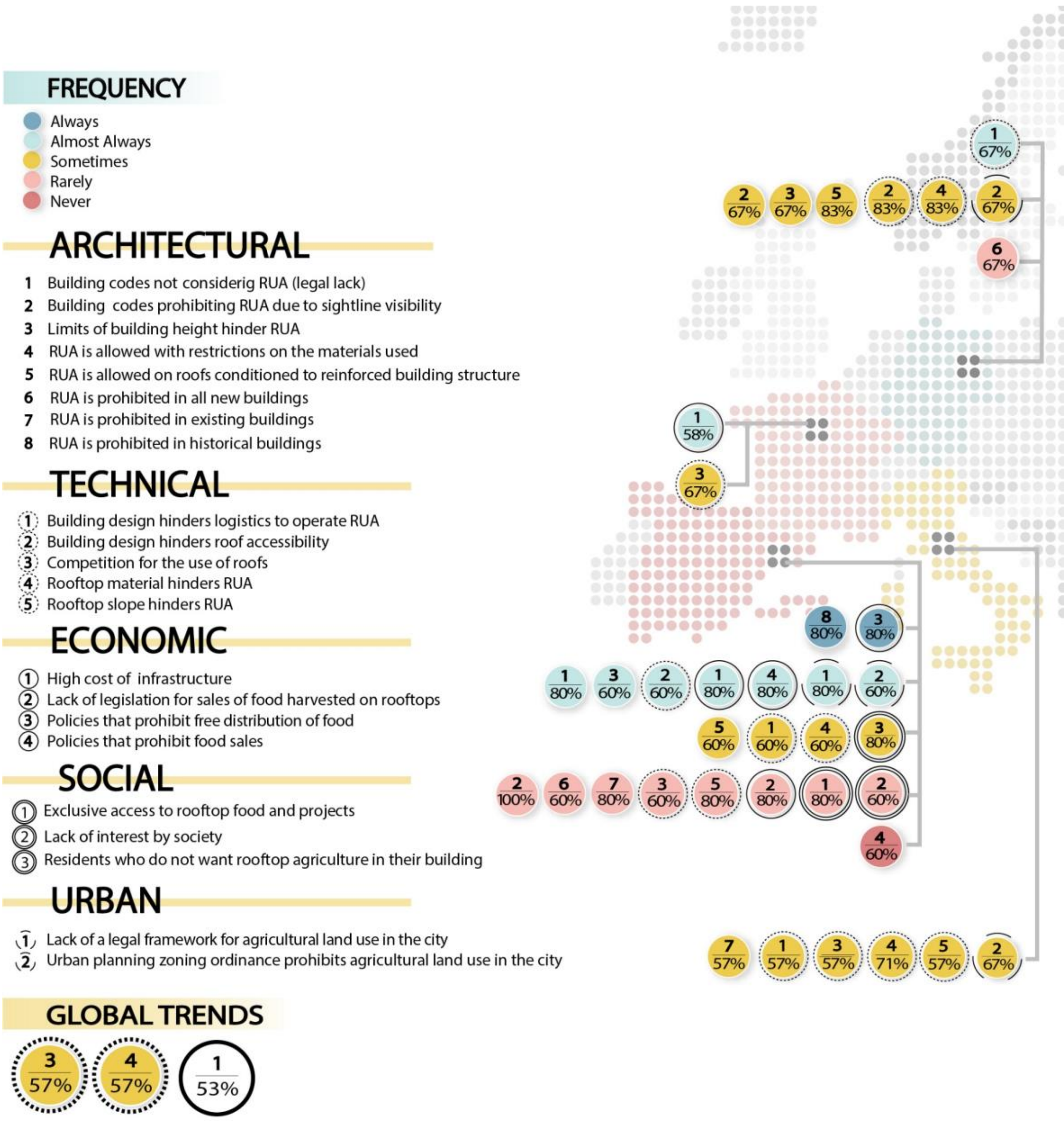

Figure 6.7. Barriers and perceived frequency with which they appear for integrating RUA in four European cities

6.4 Discussion

This study has provided an exploratory overview of key factors, contextual factors, policies, and barriers associated with the integration of RUA based on stakeholders' perceptions in four European cities. It contributes to the literature on stakeholders' perceptions of RUA using a framework that can be applied extensively in EU cities. These perceptions likely shape the development of RUA agriculture practices and projects. In the following sections, the most relevant factors, policies, and barriers that may promote or hinder the integration of RUA are discussed.

6.4.1 Potential key factors for integrating RUA

Technological innovation, *food production* and *research* were factors identified in this study as relevant for integrating RUA that had not been previously reported (Cerón-Palma et al., 2012; Sanyé-Mengual et al., 2016; Specht et al., 2016a; Specht & Sanyé-Mengual, 2017). This is likely due to the increasing relevance of RUA in the cities involved in the study, thanks to recent supporting policies and the development of new RUA projects, allowing stakeholders to identify both existing and new key factors. The *research* factor, scarcely addressed in the previous literature, was repeatedly mentioned, possibly as a result of the involvement of academics in the study. RUA, therefore, seems to be an opportunity for developing research projects. Other factors identified in the study that have also been previously mentioned in the literature include *environmental purpose*, *social community building* and *educational functions* of RUA (Sanyé-Mengual et al., 2016; Specht et al., 2016a). A relevant contribution concerns to the perception about the *economic* factor was perceived as being of "little relevance" (67%) by the stakeholders from Berlin and "not relevant" (80%) by participants from Barcelona, despite the proven evidence on the crucial role that economic considerations may play in the viability of RUA initiatives (Cerón-Palma et al., 2012; Specht et al., 2016; Specht & Sanyé-Mengual, 2017).

6.4.2 Context factors and their perceived degree of hindering or promoting RUA

A relevant contribution is a perspective concerning *high urban land costs* which are perceived as a "promoting" factor of RUA. This posture is the opposite of the study conducted by Orsini et al. (2020) about urban agriculture and was not identified in previous RUA studies (Cerón-Palma et al., 2012; Sanyé-Mengual, Anguelovski, et al., 2016; Specht et al., 2015; Specht et al., 2016a). This finding could be due to the expansion of UA experiences in recent years. *Cultural values*, *social cohesion*, the creation of wasted areas into *productive spaces in urban areas*, and the interaction of *rural activities taking place in urban areas* rather than looking separately, showed correspondence with previous works where similar factors had been identified as opportunities for integrating UA (Cerón-Palma et al., 2012; Sanyé-Mengual et al., 2016; Sanyé-Mengual et al., 2018a). One difference to highlight was regarding *pollution*, perceived as both a "hindering" (Barcelona and Paris) and a "promoting" (Bologna) factor. Previous studies in Barcelona and Berlin had reported pollution as a barrier for RUA development (Sanyé-Mengual et al., 2016; Specht et al., 2016a). These differences could be associated with the field of expertise of the participants; however, this hypothesis was not addressed in this study, and a more in-depth analysis is required for its validation. The perception of RUA has been associated with health risks related to pollution, although the perceived risks have been partly negated by the results of scientific analyses (Antisari et al., 2015). According to a recent study, heavy metal concentrations in lettuce growing in open-air systems located in high-traffic areas of Barcelona are below the EU-legislated level (Ercilla-Montserrat et al., 2018). However, research on this issue is still recent, and further empirical evidence is necessary to validate the findings in different contexts. This study further revealed that stakeholders perceived the *cost of water* as a "hindering" factor, which had not been identified previously (Cerón-Palma et al., 2012; Sanyé-Mengual et al., 2016; Specht et al., 2015; Specht et al., 2016a; Specht & Sanyé-Mengual, 2017; Zambrano-Prado et al., 2021). Water for irrigation of crops can be expensive in urban areas. In addition, water is an increasingly scarce resource. Different systems can be implemented to optimize water use, for example, leachate recirculation or the integration of rainwater harvesting systems. Thus, special attention and exploration of possible alternatives are needed.

6.4.3 Policies and their perceived effects on hindering or promoting RUA

Policies related to *food trade* are a constraint for developing RUA. As other cities have already identified, restrictions on the sale of products from urban farms may limit products grown locally. Some cities (e.g., New York City, Chicago, Toronto) have addressed this restriction by changing policies and the zoning code (Fletcher et al., 2012). Barriers regarding *architectural* and *urban codes* were identified in this work. These findings are not new and still represent legal constraints for RUA, even in cases where UA is highly compatible with urban development strategies. A lack of consistency in various legal fields, such as hygiene and food processing laws, was reported in the previous literature. Nevertheless, major concerns refer to building laws, which are considered too strict and difficult to understand. In this sense, stakeholders perceived various uncertainties and regulatory gaps (Specht et al., 2016a). In the case of Paris, the city council has made some changes in the Paris Local Urban Plan (Paris City Council, 2018) to be more "friendly" to RUA projects. However, according to the results from this study, there is still a perception that *architecture* and *urban planning laws* "hinder" RUA development. In addition, *financial incentives*, the *development of new technologies*, *education*, *food production* and local policies such as the *Milan urban food policy pact* and *Parisculteurs* program were identified in this study as "promoting" RUA. Policies targeting the *development of new technology* not found in the previous literature were also identified by the stakeholders in this study, possibly due to the involvement of academics. This finding is relevant for exploring techniques, procedures, and resource efficiencies for RUA. The importance of *educational* benefits has already been determined in the international literature (Cerón-Palma et al., 2012; Specht et al., 2015; Specht et al., 2016a). RUA could be integrated as an educational strategy for promoting environmental education, considering that many schools currently have meal services (Nadal et al., 2018) and, according to the main goal of The Global Education 2030, for developing sustainability competencies as a core of Education for Sustainable Development (Leicht et al., 2018). Sustainable benefits have also been extensively recognized (Cerón-Palma et al., 2012; Sanyé-Mengual et al., 2016; Specht et al., 2015; Specht., 2016a), although their frequency varies across cities. Contrary to a few years ago, currently in Barcelona, local environmental policies such as Barcelona's Climate Plan 2018-2030 integrate the inclusion of RUA, with the ambitious objective of reaching 34,100 m^2 of green roofs, walls, and facades by 2030. The Climate Plan 2018-2030 also includes drawing up bylaws to promote productive roofs and consolidate an annual green roof contest. In addition to developing the winning projects, which are not restricted to ornamental plants, projects could also integrate food production (Barcelona City Council, 2017). Additionally, the Paris Climate Action Plan (2018) includes part of the "Objective 100 Hectares" initiative, one-third of which will be devoted to UA located on green roofs and walls (City of Paris, 2018). Differences between cities were found. This is especially true for the perceived effect of *urban policies* on RUA expansion. Assumptions for these differences could be due to the fields of expertise and personal experience with RUA. However, to confirm this hypothesis, a broader analysis is required.

6.4.4 Barriers for integrating RUA

Architectural barriers

Constraints for integrating RUA in historical buildings and the *limits on the height of buildings* according to building codes were identified in this study as barriers to RUA development but had not been reported before, perhaps due to the recent growth of RUA experiences. Regarding the limits on the height of buildings, since the implementation of the Parisculteurs program (Paris), the city council has changed urban regulations to allow farming on rooftops even when the building exceeds height limits (Brin et al., 2016). Nevertheless, according to stakeholders' perceptions, this barrier still applies. In Barcelona, RTGs cannot be built on some rooftops due to height/volume restrictions (Metropolitan area of Barcelona, 2018). Among the constraints for RUA integration, it was mentioned that *building codes did not consider RUAs* and the *need for building structure reinforcement*. Indeed, building overloading and the need for reinforcement (Cerón-Palma et al., 2012; Sanyé-Mengual et al., 2016) are still major barriers. Currently, many buildings may not have a suitable structure or load-bearing capacity for RUA (Toporova, 2018), which may also have economic repercussions due to the cost of building reinforcement and the need for professionals to develop and execute such projects.

Technical barriers

Building designs to operate RUA and the *difficulties of roof access* were mentioned as factors that "constrain" RUA development. Cerón-Palma et al. (2012) also identified the complexity of adapting or renovating existing buildings; in this sense, it is essential to identify how users would access the roof spaces considering safety norms. In general, the technical adaptations necessary to operate RUA can lead to extra costs and limit the economic feasibility of projects. *Competition for integrating other systems and/or functions on roofs* is still present, as reported in previous works (Cerón-Palma et al., 2012; Sanyé-Mengual et al., 2016). However, current practice demonstrates that the integration of multiple systems/functionalities can also take place in parallel. In Barcelona, the RTG Lab Fertilecity integrates a rainwater harvesting system (RWHS) for crop irrigation, reaching 100% water self-sufficiency (Sanyé-Mengual et al., 2014). Five RUA projects recently built integrate RWHS and photovoltaic (PV) systems (Barcelona City Council, 2017). Thus, RUA, RWHS, and PV systems can coexist, providing significant benefits (Benis et al., 2018; Corcelli et al., 2019; Toboso-Chavero et al., 2018).

Economic barriers

Regarding economic categories, stakeholders perceived that the *high cost of infrastructure* is a major barrier; previous studies also reported this constraint (Cerón-Palma et al., 2012; Sanyé-Mengual et al., 2016). Such barriers can be addressed with the support of financial policies and incentives, such as those already implemented in Barcelona and Paris. However, the initial investment goes beyond the financial cost, since maintenance of this kind of infrastructure is also expensive and constitutes an additional barrier during the operation stage (Zambrano-Prado et al., 2021). Therefore, for RUA that are successful and do not turn into short-lived projects, maintenance costs beyond the initial costs must be studied and considered. *Food sales policies* are related to urban land zoning ordinances, and together with the perception of *high-cost infrastructure*, can lead investors with commercial interests to easily lose interest. If there is no specific legislation for the trade of products grown within the city, it is difficult to integrate large-scale RUA projects. Fletcher et al. (2012) recognized restrictions by municipalities on sales of locally grown products in cities. To address this barrier, some cities have made policy changes, especially in North America. In 2012, the Berkeley Planning Commission adopted the definition of "Non-Processed Edibles", which allowed the production of different kinds of food products within urban areas and their sale in residential districts (Fletcher et al., 2012).

Social barriers

As in previous barrier categories, no common social barrier was found in the target cities. Compared to other barriers, social aspects were associated with fewer constraints. The survey revealed that *exclusive access to food growing on rooftops*, *exclusive access to developing RUA*, a *lack of interest by society in RUA projects* and *limited acceptance by residents of RUA on their building* are not frequent. However, during the workshop, stakeholders manifested their concerns about these social barriers. A risk that large companies may transform RUA into an exclusively profit-oriented (Specht et al., 2016a) initiative and, thus, aggravating social disparities in accessing systems and products (Sanyé-Mengual et al., 2016) have been identified by stakeholders in the previous literature. These risks could also be drivers of green gentrification in neighborhoods. Currently, however, this risk does not seem to be a major concern among stakeholders.

Urban planning

Urban planning codes that do not contemplate urban agricultural land use are still barriers. Castillo et al. (2013) identified barriers related to zoning codes, such as a lack of clear ordinances that are friendly to agriculture. In Singapore, urban planners included rooftop farms in the definition of urban green spaces and diversified the classification of agricultural land use, allowing this activity in urban areas (Diehl et al., 2020). Additionally, cities in the U.S., such as New York and Chicago, were included (City of Chicago, 2020; The New York City Council, 2010; Urban sustainability exchange, 2011). Of the cities involved in this study, in Barcelona, the General Metropolitan Plan does not allow agricultural activities inside the city, effectively making the commercialization of food produced in the city illegal. In the case of Paris, programs to encourage UA have been launched, which may allow agricultural activities in the city, while in Bologna, the workshop findings indicate that agricultural activities are not allowed in the city.

6.5 Conclusions

This paper explores the perceived key factors, contextual factors, policies, and barriers to integrating RUA by ranking their relevance and the frequency with which they are presented. It also revisits the concepts associated with environmental, architectural, technological, social, legal, economic, and urban planning from the perspective of stakeholders from four European cities (Barcelona, Berlin, Bologna, and Paris).

In all cities involved in the workshop, policies exist to support UA, often resulting in RUA experiences implemented by or involving local government. However, an explicit and singular public policy for RUA practices is still missing.

Major key factors that promote the development of RUA, not previously reported, include technological innovation, growing local food, research activities, and the high cost of urban land in cities. Major factors that hinder RUA were identified as the cost of water and pollution (Barcelona and Paris). While most of the participants from Bologna (70%), identified pollution as promoting factor. The cost of water appears as a new barrier, and thus is a relevant topic for future studies and for efforts to find ways to respond to this constraint, including technological innovation, research, and policy creation. Regarding pollution, the need for disseminating proper information and conducting a deeper study on perceptions of the effects of pollution, as well as establishing quality management and quality control for crop production, are highlighted.

Policies targeting sustainability were found to be common in all cities as "promoting" factors. Currently, and contrary to some years ago, there are already policies that promote RUA for environmental purposes, such as Barcelona's Climate Plan 2018-2030 and Paris Action Climate Plan 2019. However, there is still a lack of urban, architectural, and product sales regulations for this kind of infrastructure, which continues to make the integration of RUAs difficult. Policies related to financial incentives that are generally included in city policies, the development of new technologies for crop production systems and buildings, educational programs, policies for food production within the city, such as the Milan urban food policy pact and Parisculteurs program were all identified good examples as "promoting" RUA development. Limitations on marketing products grown within the city, as well as urban policies, continue to restrict the integration of the RUA. The inclusion of RUA in policies focused on climate change is insufficient. For the expansion and success of RUA projects, it is necessary to consider these infrastructures in the different related codes. The creation of new legislation or modifications to support RUA is necessary, especially in the South European cities studied—Barcelona and

Bologna. A flexible land use policy that allows UA in cities must be considered by urban planners as well as sales of products with production and distribution regulations. Changing regulatory barriers is a potential opportunity to create laws and programs to promote and expand RUA.

RUA faces several architectural, economic, and urban challenges that need to be addressed. The following architectural factors stand out as impediments: construction licenses in historic buildings, building codes that do not contemplate this type of infrastructure and the height limits of buildings stipulated in construction regulations, usually exceeded by RUA infrastructure. Two technical barriers were identified as major constraints: building designs that pose logistical difficulties in operating RUA and problems with roof access. In the economic category, the high cost of infrastructure and policies that prohibit food sales are major constraints. The lack of legislation regarding agricultural land use and urban zoning ordinances that prohibit agricultural activities also limit RUA integration.

Architectural and technical barriers can represent higher investment costs. Both financial incentives and business plans are needed to develop economically self-sufficient RUA projects. It was noted that access or exclusivity in projects is not a major concern. However, it is necessary to consider risks such as gentrification or commercial purposes and to study and anticipate these potential risks through legislation. The integration of urban agriculture must consider the social, educational, environmental, technological innovation and research functions that have been described as key factors for its integration in cities.

Although some differences were found between the targeted cities, these should be confirmed through more extensive research. To this end, the framework and set of statements elaborated here could be used for further data collection, allowing to analyze and characterize more stakeholder perceptions. Future research should be conducted on a larger sample of participants to confirm the empirical differences between cities.

Chapter 7

Perceptions on barriers and opportunities for integrating urban agri-green roofs: A European Mediterranean compact city case

CHAPTER 7 - Perceptions on barriers and opportunities for integrating urban agri-green roofs: A European Mediterranean compact city case

This chapter is based on the following journal paper:

Zambrano-Prado, P., Pons-Gumí, D., Toboso-Chavero, S., Parada, F., Josa, A., Gabarrell, X., & Rieradevall, J. (2021). Perceptions on barriers and opportunities for integrating urban agri-green roofs: A European Mediterranean compact city case. Cities, 114, 103196. https://doi.org/10.1016/j.cities.2021.103196

Abstract

The main objective of this study is to analyze the perceived barriers and opportunities with regard to the implementation of urban agri-green roofs (UAGR) in cities. The case study was conducted in Barcelona, a Mediterranean compact city. The World Café method was used in this work. Five categories of barriers and opportunities were discussed (social, environmental, legal/administrative, technological/architectural, and economic) by interdisciplinary stakeholders.

A total of 129 barriers and opportunities were identified. The main barriers identified were as follows: the lack of information and social cohesion regarding UAGR projects; the Mediterranean climate; the lack of specific regulations and protocols; the initial investment; and the pre-condition of the roof and its load bearing capacity. The main opportunities were social cohesion; improved life quality; new specific regulations; the profits derived from UAGR projects; and aesthetic improvement.

The UAGR's scale of impact results showed a homogeneous distribution between "building" and "city", while the "global" scale remains residual. Regarding the stage of the UAGR life cycle at which barriers and opportunities emerge, the results highlight how most opportunities appear during the "use" stage of the roof, whereas barriers do so during the "project" stage.

Keywords

Rooftop agriculture, Stakeholder's perception, World Café, building

7.1 Introduction

The global population has increased rapidly since 1950. According to the projections, 68% of the world's population will live in cities by 2050 (United Nations, 2018a).

Urban areas have increased the pressure and exploitation levels imposed on the ecosystems both at local and global scale as they are responsible directly or indirectly for approximately 75% of global energy consumption and 80% of greenhouse gas (GHG) emissions (Ash et al., 2008), exerting high impacts on levels of atmospheric pollution and the rising demand for natural resources (Cerón-Palma et al., 2012). In addition, the built urban environment contributes to the urban heat island (UHI) effect; specifically, temperatures in urban areas can be up to 5–12 °C warmer compared to surrounding rural areas (J. S. Lee et al., 2014), contributing to climate change.

Apart from the above-mentioned problems, cities with high population density, the so-called compact cities, also experience important issues related to a lack of space and more specifically green spaces. In this sense, real estate speculation, increased population density, spatial limitations, and the high competition in relation to land in urban areas have implicitly led to a decrease in the available green space surface per capita, demonstrating the need for new strategies to compensate for that deficit (Tappert et al., 2018). Given the multiple benefits at the social, economic, and environmental levels provided by green spaces and the growing concern with regard to the creation of sustainable cities towards an improved quality of life, there is significant interest and need to enhance such spaces (Taylor & Hochuli, 2017); however, the spatial limitations and high competition in cities for space make opportunities for greening increasing difficult. In this sense, rooftops are relevant to the transformation from underused spaces to green and productive spaces (Toboso-Chavero et al., 2018).

7.1.1 Rooftop urban agriculture functionalities and experiences in cities

Rooftop urban agriculture (RUA) in cities with high population densities has multiple functionalities: it generates new agricultural spaces, represents an alternative to the current value chains about meeting the demand for food in urban areas, and serves as an ideal tool to cover cities' food needs by improving a city's self-sufficiency, reducing its dependence on foods that must be shipped in from a distance and the derived costs and contribute to a more circular urban food production system and developing a fundamental role in other areas of city life (Nadal et al., 2018; Sanyé-Mengual et al., 2016). Further, its benefits can be extended to addressing issues of psychological and physical health, social cohesion, economic development, urban and landscape planning, and sustainability (Azunre et al., 2019; Cerón-Palma et al., 2012; Sanyé-Mengual et al., 2016; Specht & Sanyé-Mengual, 2017). It also has a relevant impact in terms of increasing biodiversity and habitats that are more suited to the life of flora and fauna in cities, creating green spaces and serving as an ideal tool for education and environmental awareness. Furthermore, increasing green spaces in cities by implementing RUA has been demonstrated to be one of the key approaches for mitigating UHI effects (Alexandri & Jones, 2008; J. S. Lee et al., 2014; Susca et al., 2011). In addition, RUA decreases energy consumption due thermal properties and insulating effects, creating energy savings for both cooling and heating buildings (Muñoz-Liesa et al., 2020; Nadal et al., 2018; Susca et al., 2011).

7.1.2 City policies: green and urban agriculture roofs

Due to the multiple benefits from green roofs (GR), urban policies have been implemented in a global context, and the most representative incentive policies correspond to subsidy (53%)

and adopting bylaws (15%). Most of these policies are presented in European cities (79% subsidy and 23% bylaw) and North American and Asian cities (12% and 9% subsidy and 32% bylaw) (Liberalesso et al., 2020).

Regarding North Europe, in 1996, the city of Basel (Switzerland) started to promote green roofs via subsidy programs (Climate adapt, 2015). In the Netherlands, several municipalities support the construction of green roofs requiring minimum criteria to be able to apply for subsidies (Almelo, 2020; Amstelveen, 2019; Amsterdam, 2020; Den Bosch, 2020; Groningen, 2020; Hengelo, 2020; Leeuwarden, 2020; Leiden, 2020). In Germany, at least 48 cities provide financial support (Technical and Environment Administration Copenhagen, 2016) that primarily covers 50% to 60% of the green roof cost (Berardi et al., 2014; Grant, 2018).

In the United States (USA), many cities (Austin, Baltimore, Milwaukee, Minneapolis, Philadelphia, New York City (NYC), Portland, Seattle, and Washington) offered financial support (Berardi et al., 2014). For example, Chicago supports up to 50% of the cost if the green roof covers greater than 50% of the net roof area (Adaptation Clearinghouse, 2015; Berardi et al., 2014).

Singapore encourages the installation of green roofs by subsidizing up to 50% of the cost for both residential and commercial buildings; green roofs must be maintained for at least five years after construction (Singapore Government, 2020).

Some cities in North Europe have approved changes in building, construction (e.g., Basel, Berlin, Stuttgart, and Copenhagen) and land-use planning codes (for example in London) to require bylaw green roofs. At the country level, France integrated a national law to require green roofs or solar panels in all new buildings located in commercial zones (The Guardian, 2015).

Other cities around the world also have adopted bylaws on the construction of green roofs on new buildings, Toronto (Canada) was the first city in North America to integrate these bylaws (City of Toronto, 2009). In Asia, the city of Tokyo requires green roofs on both private and public buildings (*C40 Cities*, 2015). More recently, in South America, the cities of Guarulhos and Recife in Brazil and Cordoba in Argentina also required green roofs (Grant & Gedge, 2019; *Law No 7031*, 2012; Liberalesso et al., 2020).

Regarding policies for integrating RUA, New York City, Washington DC, Chicago, Toronto, Singapore, and Paris initiated pioneer programs related to food production on building rooftops. The NYC council included the use of rooftops for food production in local plans (The New York City Council, 2010). Chicago reformed city laws regarding UA, allowing urban farms on rooftops (City of Chicago, 2020; Urban sustainability exchange, 2011). In Singapore, urban planners included rooftop farms in the definition of urban green spaces and diversified the classification of agriculture land use, allowing this activity in urban areas (Diehl et al., 2020). Through the Parisculteurs program, Paris supports rooftop urban agriculture projects, and more than 48 projects have been developed on both public and private buildings since the first call in 2016 (Ville de Paris, 2019). The Barcelona city Council promoted The First Green Roof Contest in 2017. Winning projects received a subsidy up to 75% of the construction cost. The requirements stipulated that a minimum of 50% of the roof area or 200 m^2 had to be green, especially (but not only) on residential roofs. Subsidies were not restricted to the integration of ornamental plants, and projects could also integrate food production, rainwater harvesting, and renewable energy systems (Barcelona City Council, 2017).

As we can observe, cities worldwide are adopting green roof policies, especially North Europe, North America, and some Asian cities. In the case of South Europe, information in the literature regarding policies to support RUA projects are lacking. In Barcelona, recent subsidies have been emerged to encourage the implementation of these types of projects. However, the lack of promotion, specific laws, legal procedures, and urban codes can act as barriers to integrate these policies in cities that recently started to adopt support.

7.1.3 Approach for identifying green roofs and rooftop urban agriculture barriers and opportunities

As observed in the last section, legal barriers, such laws, and administrative procedures, are an important issue regarding RUA implementation. In addition to legal barriers, others barriers and opportunities, such as social, environmental, economic, aesthetical, and technological barriers, have been identified (Cerón-Palma et al., 2012; Heath, 2009; Hendricks & Calkins, 2006; Sanyé-Mengual et al., 2016; Sarwar & Alsaggaf, 2020; Specht al., 2016a; Specht & Sanyé-Mengual, 2017; X. Zhang et al., 2012). Table 7.1 presents some studies conducted to identify barriers and opportunities for implementing GR and RUA from the point of view of stakeholders or citizens.

Table 7.1. Studies of barriers and opportunities from stakeholders' perceptions.

City	System	Data collection			Participant			Key approach	Reference
		I	S	Q	AS	NAS	C		
Barcelona (Spain)	RTGs		●		●			Barriers and opportunities	(Cerón-Palma et al., 2012)
Barcelona (Spain)	URF	●			●	●		Barriers and opportunities	(Sanyé-Mengual et al., 2016)
Berlin (Germany)	ZFarming	●			●	●		Benefits and risks	(Specht, Siebert, et al., 2016)
Berlin (Germany) and Barcelona (Spain)	URF	●			●	●		Risks	(Specht & Sanyé-Mengual, 2017)
Bologna (Italy)	UA*			●			●	Social acceptance	(Sanyé-Mengual, Specht, et al., 2018)
Chicago and Indianapolis (USA)	GR			●	●	●		Cost, benefits, barriers, and incentives	(Hendricks & Calkins, 2006)
Hong Kong (China)	GR	●		●	●	●		Barriers	(X. Zhang et al., 2012)
Lahore (Pakistan)	GR			●			●	Motivation to adopt GR	(Sarwar & Alsaggaf, 2020)
Texas (USA)	GR	●			●			Barriers and facilitators	(Heath, 2009)

The system studied included rooftop greenhouses (RTGs), rooftop open-air farming and urban rooftop farming (URF), all possible types of urban agriculture in and on buildings (ZFarming), and urban agriculture (UA),* including rooftop agriculture and green roofs (GR). Data collection was performed using interviews (I), seminar of discussions (S), and questionnaires (Q). Participants from studies included stakeholders already actively involved in green roofs or rooftop agriculture projects (AS), stakeholders not actively involved but considered important due to their knowledge (NAS), and citizen or residents (C).

As reflected in Table 7.1, the most frequent methods used for data collection included interviews and questionnaires; most of these studies included different and multidisciplinary participants specialized in diverse fields, including city planning, construction, public administration, research centers, agronomy, food distribution, sales, associations, and activist institutions from both private and public institutions (Heath, 2009; Sarwar & Alsaggaf, 2020; Specht, Siebert, et al., 2016; Specht & Sanyé-Mengual, 2017). In contrast, other works focused on developers, city officials, and architects (Heath, 2009; Zhang et al., 2012). Citizen and residents perceptions also have been the center of studies (Hendricks & Calkins, 2006; Sanyé-Mengual et al., 2018b; Sarwar & Alsaggaf, 2020). Perspectives focused on building owners and architects (Hendricks & Calkins, 2006) are minimally reported.

Studies that consider data collection methods where stakeholders interact and share their knowledge and experiences (e.g., focus groups, Knowledge network, or World Café) to address barriers and opportunities regarding the implementation of GR and RUA projects are lacking.

7.1.4 World Café method

World Café is based in a constructive conversation related to critical questions and collaborative learning. It assumes that the knowledge that we are searching is already present (Fouché & Light, 2011). This participatory method is particularly powerful due the informal environment, and its structured dialogue focuses on questions relevant to the participants and promotes rounds of information exchanges between the stakeholders that results in a cross-pollination of ideas (Estacio & Karic, 2015; Fouché & Light, 2011; Prewitt, 2011). This method has been used in a variety of settings to identify and analyze barriers and opportunities and other research aspects. For example, in London, the method was used as one part of 'Well London", a five-year program to promote the health and well-being of their residents (Bertotti et al., 2012). In addition, the method has been used in deprived urban neighborhoods to analyze how residents view 'community' and the barriers to community cohesion (Bertotti et al., 2012). The method has been used in higher education to encourage reflection on internationalization (Estacio & Karic, 2015). In Ireland and the USA, the method was used for prioritization of marginalized communities (MacFarlane et al., 2017). In Genova, it was used to identify potential areas of research for measuring sustainability performance (Silva & Guenther, 2018). World Café was employed in secondary school classrooms to identify barriers and opportunities to implement an educative program (Cosby et al., 2019). The method was also used in Ireland to explore barriers and opportunities to enhance research among pharmacists (Kavanagh et al., 2020).

In this study, the World Café technique was chosen to elicit barriers and opportunities from the stakeholders because this method allows participants to share their thoughts and opinions in an open, welcoming, and social environment. Participants feel comfortable in this setting, so this method provides an opportunity for mutual insight and innovative thinking and creates possibilities for action (Estacio & Karic, 2015; Fouché & Light, 2011).

Additionally, World Café has been used effectively in analyzing barriers and opportunities (Bertotti et al., 2012; Cosby et al., 2019; Kavanagh et al., 2020). This method exhibited a significantly higher positive effect compared with traditional strategy workshops (W.-L. Chang & Chen, 2015).

Worldwide, GR and RUA are increasingly used in cities, primarily as a part of air quality, climate resilience, and biodiversity strategies. Various policies and regulations in promoting green roofs and rooftop agriculture have been developed and introduced in North Europe (particularly Germany and the Netherlands) and North America. These contexts represent cases with cold winters and fewer sun hours compared with other regions, such as the South of Europe where climate conditions are more favorable for rooftop agriculture production (Sanyé-Mengual, Anguelovski, et al., 2016).

On the other hand, regarding case studies, the literature indicates a high potential of roofs (2,608 ha) suitable for GR and RUA implementation in Barcelona city (Urban Ecology Agency Barcelona, 2010). Even with this potential, currently only the 0.36% of Barcelona's roofs are GR and RUA (Urban Ecology Agency Barcelona, 2010).

Previous works show a lack of policies and incentives to encourage GR and RUA projects in Barcelona; however, the recent Climate Plan 2018-2030 considers GR and RUA implementation to mitigate and adapt to climate change and improve the quality of life (Barcelona City Council, 2018a). In this sense, the municipality of Barcelona recently started to encourage these types of facilities through the first contest called The First Green Roofs Contest. In this sense, the incentives for these projects appear to be very recent compared with other geographic regions.

Few studies have examined barriers and opportunities of GR and RUA projects in Barcelona, and these works were performed before the first subsidy initiative was launched. Furthermore, data collection was performed by interviews, and discussions were held in seminars. These methods have some limitations for generating insights from participants about their knowledge and experiences. Other methods, such as the World Café, can be used as a platform to gather collective knowledge to address these types of subjects.

For this work, the term urban agri-green roofs (UAGR) will be used to refer both green roofs without and with horticulture activities considering open-air as a production system.

The study makes relevant contributions with respect to previous research in this field. First and contrary to most barriers-opportunities studies and policies developed in North Europe and North America, this research focuses on Southern European, where incentives to support UAGR have recently emerged. For this reason, the contributed findings are important to provide a solid basis for the policies that aid in the development of sustainability in cities moving towards the implementation of these policies, such as Barcelona. Second, the use of World Café is an effective method for collecting data on perceptions of barriers and opportunities, but it has not been used on previous research in Barcelona. Third, this study assessed the personal experience of the stakeholders with The First Green Roof Contest and their real experience in the different stages of the project- construction-use process. Based on the above perspectives, this is a new approach in this field of study.

Finally, the work explores new perspectives regarding not only the identification of barriers and opportunities but also the stage of the life cycle (project-construction-use) of UAGR and the scale where barriers and opportunities are presented, representing an original and integrated approach to the topic to be investigated.

In this regard, the aim of this research is to identify the perceptions of barriers and opportunities for implementing UAGR projects in a Mediterranean compact city. In this sense, the specific objectives are as follows:

1) To identify potential social, environmental, legal/administrative, technological/architectural, and economic barriers and opportunities for integrating UAGR.

2) To determine the scale, including building, city, or global aspects, of potential barriers and opportunities are presented.

3) To classify the perceptions of potential barriers and opportunities within a UAGR project's life cycle stage: project-construction-use.

7.2 Methods

Five stages were considered to address the work: (1) case study, (2) participants' definitions, (3) identification of barriers and opportunities, (4) data collection, and (5) data analysis. These stages are described in detail in the following subsections. Figure 7.1 presents the workflow of this research.

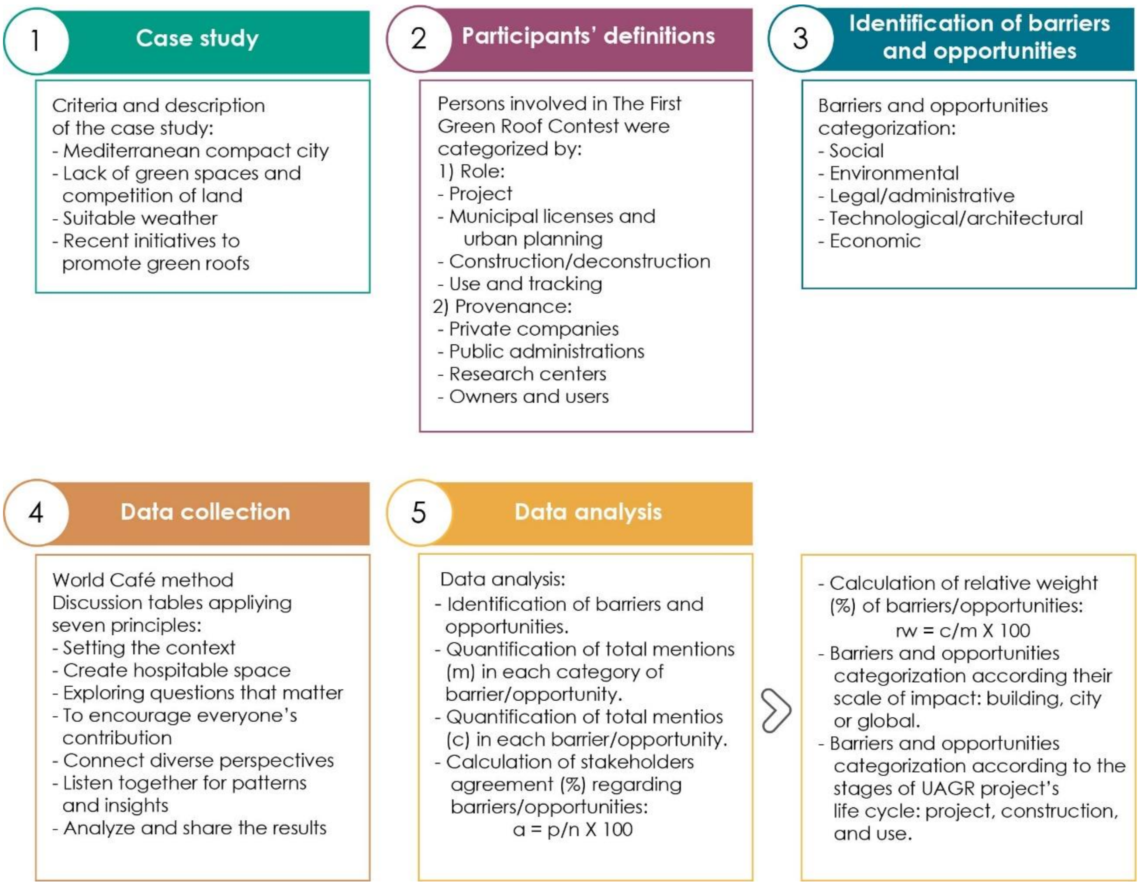

Figure 7.1. Workflow to identify potential barriers and opportunities regarding UAGR implementation. Percentage of agreement (*a*) where *p* represents the number of stakeholders who identified the same barrier or opportunity and *n* is the total number of participants in the sessions. Relative weight (*rw*) expressed in percentage where c is the total times that each barrier or opportunity was mentioned and m the total mentions in each barrier/opportunity category.

7.2.1 Case study

The city of Barcelona (Spain) was chosen as a case study based on the following criteria:

Mediterranean compact city. According to macro definitions, countries of Southern Europe share some geopolitical and socioeconomic characteristics (Leontidou, 1990) and advanced socio-economic and political realities distinguish by similar urban issues compared with North African and Middle Eastern Mediterranean cities (Pace, 2002). Regarding micro definitions, the typical elements of many Mediterranean cities were defined as follows: recognizability of urban spaces, the subdivision of neighborhoods, and the continuous mix of architectural typologies. Mediterranean cities have been affected by similar problems, such as intensive housing; lack of green areas, infrastructures, and services; and intensive exploitation of soil (Leontidou, 1990; Pace, 2002). These sharing characteristics make Mediterranean cities from Europe countries comparable (Leontidou, 1990). Barcelona is considered worldwide as an example of a compact city (Parés et al., 2013; Rueda, 2007) with 1.6 million inhabitants in 101.3 km^2 (15,747 inhabitants/km^2), representing one of the most dense cities in Europe (Barcelona City Council, 2018).

Lack of green spaces and competition of land. Approximately 20% of the city's surface is occupied by densely built houses, and the city has 17.6 m^2 of green surface including Collserola Natural Park per inhabitant. Excluding this zone, the green space per inhabitant is only approximately 7 m^2 (Barcelona City Council, 2018a).

Suitable weather. Barcelona has predominant sunny weather during most of the year with average temperatures between 12 and 18°C during the winter and 20-26 °C during the summer (Barcelona City Council, 2018a). These climate conditions represent a good environment for agricultural production.

Recent initiatives to promote green roofs. Barcelona's Climate Plan 2018-2030 set the following objective: to reach 34,100 m^2 of green roofs, walls, and facades by 2030. Some of the short-term actions include to drawing up a bylaw to promote productive roofs and consolidating the annual green roof contest.

Within this background, a call of projects for The First Green Roof Contest was made in 2017. Projects could integrate UAGR, rainwater harvesting, and renewable energy systems. However, this study focuses on UAGR issues. The boundaries of the study area comprise Barcelona municipality districts, where the UAGR project winners of The First Green Roof Contest were located: L'Exaimple, Ciutat Vella, Sants Montjuic, Sarria-Sant Gervasi, Gracia, Horta-Gunardó, and Sant Andreu. In this context, this work considers public and private buildings with diverse building uses according to the participant projects, including housing, educational, offices, health, and industrial uses.

7.2.2 Participant's definition

Participants were persons involved in Barcelona's First Green Roof Contest. In this sense, participants had recent and updated knowledge of the process of implementation of UAGR (from project to use stages). Stakeholders were categorized according to two main criteria: 1) the specific role that they play in the stages of the project's life cycle regarding the implementation of UAGR, (a) project, (b) municipal licenses and urban planning, (c) construction/deconstruction, and (d) use and tracking; and 2) their provenance, including (a) private companies (PC), (b) public administrations (PA), (c) research centers (RC), and (d) owners and users (OU). Figure 7.2 shows categorization of participants.

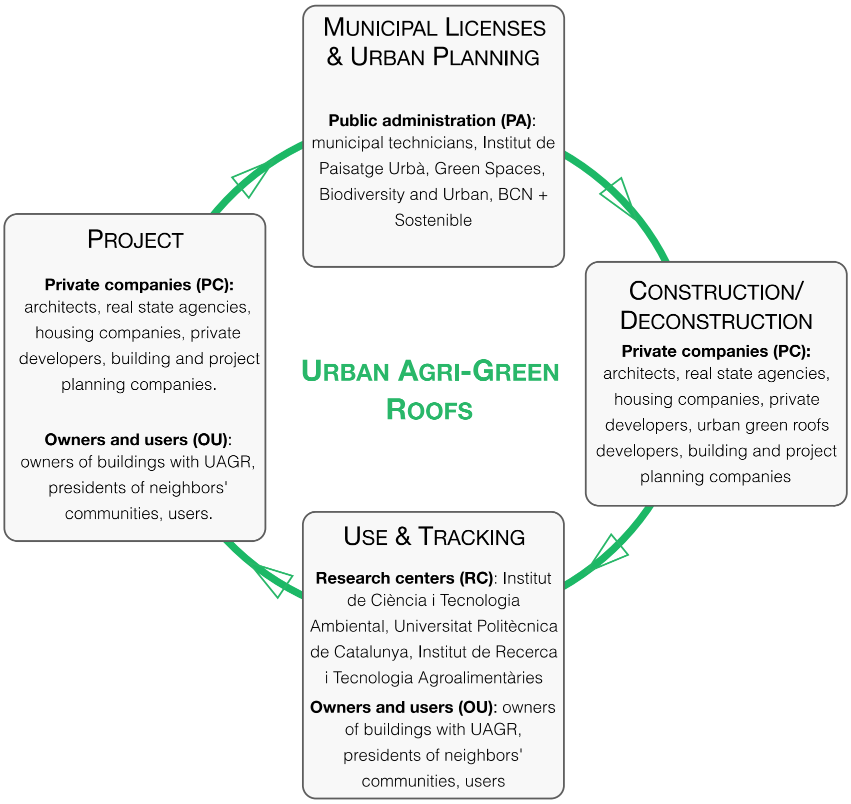

Figure 7.2. Stakeholders involved in the stages of a UAGR.

7.2.3 Identification of barriers and opportunities

Five categories of barriers and opportunities were identified based on the previous literature related to rooftop urban agriculture perceptions (Cerón-Palma et al., 2012; Nadal et al., 2018; Sanyé-Mengual et al., 2016; Specht & Sanyé-Mengual, 2017): (1) social, (2) environmental, (3) legal/administrative, (4) technological/architectural, and (5) economic.

7.2.4 Data collection

The data collection was performed using the World Café method (The World Café Community Foundation, 2015) by applying the seven principles of the method.

As a first step, the session began with registration. Each participant was supplied with a label with name and a code according to their stakeholder category. After registration, a welcome presentation was made followed by an explanation of the purpose of the conversation and how the workshop would proceed.

The workshop comprised two sessions (performed in one day) and five rounds (in each discussion table) by session. The first session focused on the barriers, and the second session focused on the opportunities related with UAGR. A break occurred between each session.

The room was set up with five discussion tables, each one focused on one specific barriers/opportunities category. Participants were organized into five groups (participants chose the table where they wanted to start) composed of between 4 and 5 people and one host.

Applying the World Café method principles

1) Setting the context. The topics were set by the barriers/opportunities in the five categories previously identified: social, environmental, legal/administrative, technological/architectural, and economic. The workshop was designed to facilitate the sharing knowledge and recent experiences regarding their participation in the contest through multi-directional knowledge exchange by contributing, connecting, and listening to each other.

2) Create hospitable space. An informal environment with a relaxed atmosphere was the aim, which was addressed through two main aspects: (1) comfortable space and furniture and (2) appropriate facilitators. The room for the workshop was big enough to allow five groups to work comfortably and simultaneously (an events hall of Barcelona's municipality building). The room was set up in a café style with chairs and tables; the room had a patio with natural light. Coffee and catering services were offered free of charge during all workshop sessions. Facilitators were previously trained on the goals and practice of the World Café method. Table hosts came from diverse fields related to green roof projects (one architect, one agronomist, two environmental scientists and one green roof entrepreneur). Most of the hosts had academic and research backgrounds and practiced in their specific professional field. A welcome to the table discussion and introduction were made by hosts in each round of discussion.

3) Exploring questions that matter. Discussions started with an open question that would identify key barriers and opportunities related to UAGR projects. The same question was discussed in the five tables, but each table focused on a different topic. This setup allowed stakeholders to explore the related areas around a question. The following question was discussed:

   > What are the barriers or opportunities (according to the session) related to UAGR projects?

   Each round of discussion lasted 15 min. Once the designated time expired, the participants in each table were asked to rotate and form new groups to discuss other topic; stakeholders participated in all discussion tables with different groups. If during the discussions, no contributions were made, a list of barriers and/or opportunities and based on the literature was prepared in advance and was offered to those attending to boost the discussion (see supporting information 4.1).

4) Encourage everyone's contribution. The principal aim of the table host was to facilitate dialogue, welcome each new group of participants, introduce them to the topic being discussed, and ensure that everybody's voice and ideas are heard. No limit in the number of interventions discussed by a participant was set.

5) Connect diverse perspectives. This principle was developed to provide a continuity of ideas from the table hosts who remained in the same table and used the provided notes of the previous group(s) to provide them with input into previously discussed topics.

6) Listen together for patterns and insights. The host encouraged participants to listen and pay attention to others' opinions. At the conclusion of the question, participants shared their insights and thoughts about collective patterns of knowledge. The method used aims to capture the participants' views and insights. In this sense, the goal was to be as non-disruptive as possible while simultaneously helping to maintain the informality and café-like atmosphere in the room. The host at each table recorded the responses and added notes of the narratives provided by the participants.

7) Analyse and share the results. Findings from the discussion tables were visible for everyone to view and thematically displayed on tables. Hosts and stakeholders were encouraged to view the collection of experiences and knowledge. In addition, after data analysis, a plenary session with participants was held, and results were presented in this session.

7.2.5 Data analysis

Data generated from the discussion tables were thematically organized and analyzed in Microsoft Excel ®. This process made it possible to preserve the essence and nuances of each contribution while synthesizing the ideas under the same barrier or opportunity category. The process of data representation involved the following steps:

1) Identification of barriers/opportunities: social, environmental, legal/administrative, technological/architectural, and economic.

2) Quantification of the total mentions (m) in each barrier/opportunity category: social, environmental, legal/administrative, technological/architectural, and economic.

3) Quantification of total mentions (c) in each barrier/opportunity identified.

4) Percentage of agreement. Equation 7.1 was used to obtain stakeholder agreement regarding barriers/opportunities. Where *a* is the agreement (%), *p* represents the number of stakeholders that identified the same barrier or opportunity, and *n* is the total number of participants in the sessions.

$$a = p/n \times 100 \tag{7.1}$$

5) Relative weight. Equation 7.2 was used to calculate the percentage of relative weight (*rw*) of the barrier/opportunity. Where *c* is the total mentions in each barrier/opportunity, and *m* corresponds to the total mentions in each category of barrier/opportunity.

$$rw = c/m \times 100 \tag{7.2}$$

6) Categorization of the scale of impact. This step refers to the specific area where each barrier or opportunity is presented. For this criterion, three main scales were distinguished: building (B), city (C), and global (G). A scale was assigned to each barrier and opportunity.

7) Categorization of the stages of UAGR project's life cycle. This step refers to the specific stage of the complete implementation of the UAGR process at which each barrier and opportunity appears. For this criterion, three main stages were distinguished: project (P) if the barrier or opportunity appears during the design;

construction/deconstruction (C) if the barrier or opportunity appears during the process of mounting or disassembling the UAGR; and use (U) if the barrier or opportunity appears once the UAGR has been built and has a relationship with its operation.

7.3 Results and Discussion

7.3.1 Identification of barriers and opportunities

The World Café was attended by 70% of the invited actors (24 out of 34). As mentioned above (Section 7.2.2), the segments of the participation were divided according to the role played by the stakeholders in the UAGR projects: 11 belonged to private companies (PC), 5 were involved in public administration (PA), 4 were members of research centers (RC), and 4 attended as building owners and users (OU). However, during the session, some participants left discussion tables about the economic barriers for personal reasons. Thus, the number of participants in this category were as follows: n = 22 (barriers) and n = 18 (opportunities).

During data collection, it was not necessary to use the *barriers and opportunities support list for the World Café by categories* (see the list on supplementary information) prepared to boost the discussion. A total of 59 barriers (z) were identified: 13 social, 12 environmental, 15 legal/administrative, 6 economic, 13 and technological/architectural. A total of 70 opportunities (z) were detected: 22 social, 13 environmental, 11 legal/administrative, 11 economic, and 13 technological/architectural. Figure 7.3 presents a summary of most mentioned barriers and opportunities in each category and their relative weight. The total number of mentions (t) was 317 for barriers and 297 for opportunities considering all barriers and opportunities categories. For full data see the table *complete barriers and opportunities data extracted from the UAGR World Café* from the Supporting information 4.2 and 4.3.

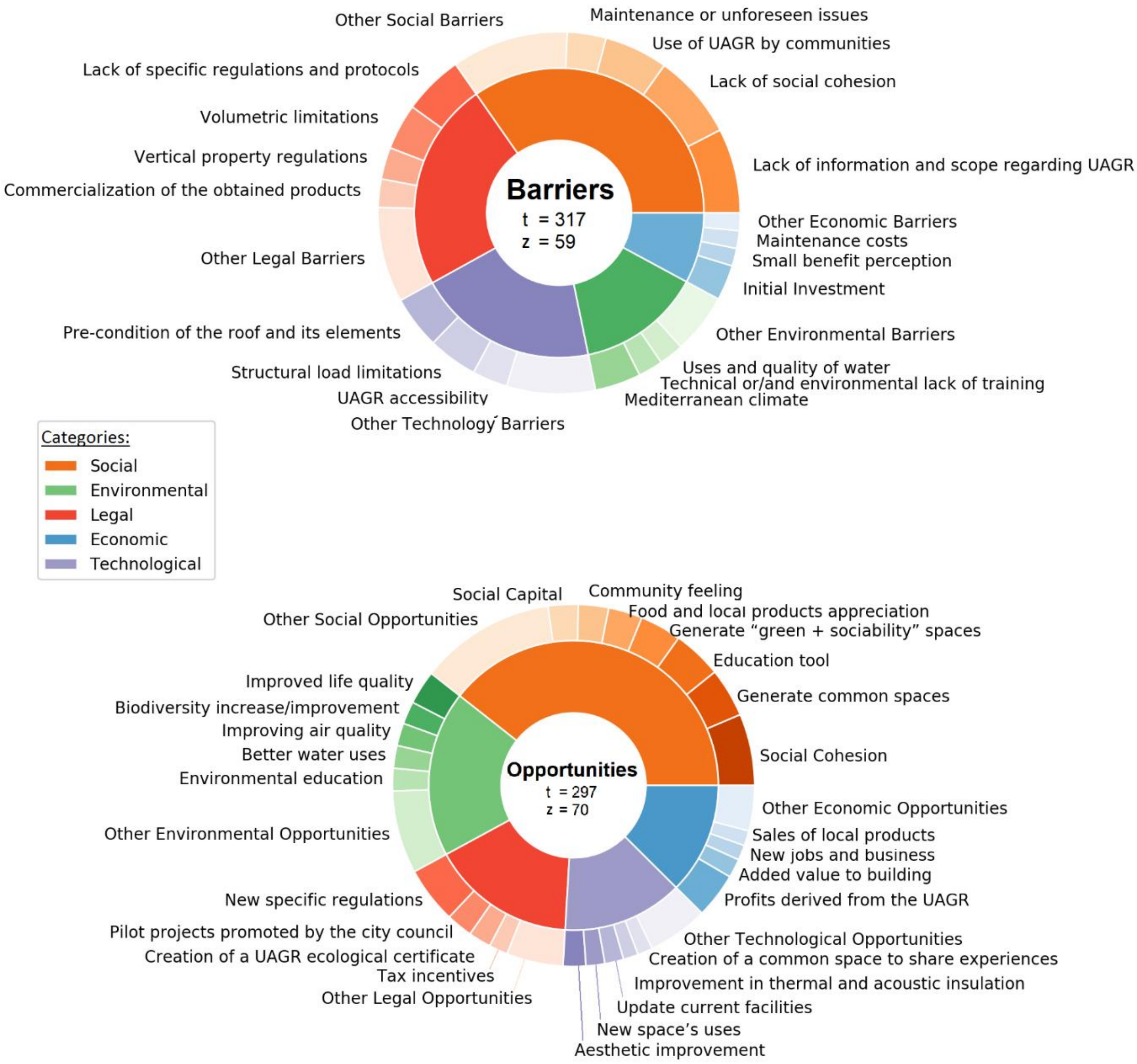

Figure 7.3. Summary of most mentioned barriers and opportunities regarding the UAGR Barcelona case study. Here, *t* represents the total number of mentions considering all barriers/opportunities categories, and *z* represents the total barriers/opportunities identified.

The total mentions in each barriers category (m) were as follow: 110 social, 74 legal/ administrative, 64 technological/architectural, 44 environmental, and 25 economic. The total mentions in each category of opportunities were as follows: 117 social, 55 environmental, 48 legal/administrative, 40 technological/architectural, and 37 economic. Result showed that not all barriers/opportunities categories have the same number of mentions. The category that generated more mentions was the social category with a total of 227 considering both barriers and opportunities, whereas the economic category generated the least comments with a total of 62.

Tables 6.1 and 6.2 present the most mentioned barriers and opportunities based on their relative weight, stakeholders' agreement, scale, and stage of UAGR life cycle.

Table 7.2. Barriers regarding UAGR implementation in the city of Barcelona. If a barrier was unanimously identified among all the stakeholders of the same type, it is represented in dark grey. If the barrier was identified by some stakeholders but not all, it is noted in light grey. If the barrier was not identified by stakeholders, it appears blank. Stakeholders were public administration (PA), private companies (PC), research centers (RC), and owners and users (OU). Scale includes city (C), building (B), and global (G). Stage of UAGR life cycle comprises project (P), construction (C), and use (U).

Category	**Barrier**	**Relative weight (%)**	**Stakeholders agreement (%)**	**Public administration (PA)**	**Private companies (PC)**	**Research centers (RC)**	**Owners and users (OU)**	**Scale**	**Stage of UAGR life cycle**
Social	Lack of information and scope regarding UAGR	22	100					C	P
	Lack of social cohesion	22	100					B	P
	Use of UAGR by communities	16	75,0					B	U
	Maintenance or unforeseen issues	10	46					B	U
Environmental	Mediterranean climate	30	54					G	U
	Technical or/and environmental lack of training	16	29					B	P
	Uses and quality of water	16	29					C	U
Legal	Lack of specific regulations and protocols	23	71					C	P
	Volumetric limitations	18	54					B	P
	Vertical property regulations	12	38					B	P

	Commercialization of the obtained products	11	33	Light grey	Light grey	Light grey	Light grey	C	P
Economic	Initial investment	40	46	Light grey	Light grey	Light grey	Light grey	B	P
	Small benefit perception	20	23	Light grey	Light grey	Light grey	Light grey	B	P
	Maintenance costs	20	23	Light grey	Light grey	Light grey		B	U
Technological	Pre-condition of the roof and its elements	23	63	Light grey	Light grey	Light grey	Light grey	B	P
	Structural load limitations	22	58	Light grey	Light grey	Light grey	Light grey	B	P
	UAGR accessibility	16	42	Light grey	Light grey		Light grey	B	P

Table 7.3. Opportunities regarding UAGR implementation in the city of Barcelona. If an opportunity was unanimously identified among all the stakeholders of the same type, it is represented in dark grey. If the barrier was identified by some stakeholders but not all, it is noted in light grey. If the barrier was not identified by stakeholders, it appears blank. Stakeholders were public administration (PA), private companies (PC), research centers (RC), and owners and users (OU). Scale includes city (C), building (B), and global (G). Stage of UAGR life cycle comprises project (P), construction (C), and use (U).

Category	**Opportunity**	**Relative weight (%)**	**Stakeholders agreement (%)**	**Public administration (PA)**	**Private companies (PC)**	**Research cente.s (RC)**	**Owners and users (OU)**	**Scale**	**Stage of UAGR life cycle**
Social	Social cohesion	16	100	Dark grey	Dark grey	Dark grey	Dark grey	B	U
	Generate common spaces	11	68	Light grey	Light grey	Dark grey	Dark grey	B	U
	Education tool	11	68	Light grey	Light grey	Dark grey	Light grey	C	U
	Generate "green + sociability" spaces	9	58	Light grey	Light grey	Dark grey	Light grey	B	U
	Food and local products appreciation	8	47	Light grey	Light grey	Dark grey	Light grey	G	U

	Community feeling	7	42	B	U
	Social capital	7	42	G	U
Environmental	Improved life quality	16	47	B	U
	Biodiversity increase/improvement	11	32	C	U
	Improved air quality	11	32	C	U
	Better water uses	11	32	B	U
	Environmental education	11	32	C	U
Legal	New specific regulations	31	79	C	P
	Pilot projects promoted by the city council	15	37	C	P
	Creation of a UAGR ecological certificate	13	32	C	P
	Tax incentives	10	26	C	P
Economic	Profits derived from the UAGR	32	67	B	U
	Added value to building	15	28	B	U
	New jobs and business	11	22	C	U
	Sales of local products	11	22	C	U
Technological	Aesthetic improvement	15	32	B	U
	New space's uses	13	26	B	U
	Update current facilities	13	26	B	U
	Improvement in thermal and acoustic insulation	10	21	B	U
	Creation of a common space to share experiences related with UAGR	10	21	C	U

Social barriers and opportunities

The notable social barriers perceived by the stakeholders with consensus among all the actors were (1) the need of information and scope of UAGR projects, such as prejudices, skepticism, lack of running examples and sensibility, little or no support by the municipality or the feeling that agri-green roofs will bring more problems than benefits, and (2) the lack of social cohesion, including low involvement of the community members in the implementation of these types of projects. Both barriers represent 44% of the total contributions in this area.

The lack of information about the real scope of UAGR projects includes the fact that fears and prejudices against such a project can influence more than the potential benefits, such as performing major work, water, and humidity or the influence of pollution on agricultural products. The absence of spirit and social cohesion affects the "project" stage insofar as the lack of predisposition by users and owners of buildings makes it difficult to implement UAGR projects. According to the registered opinions, such lack of spirit is not considered to be due to scepticism but rather various concepts, such as "social good" or "citizen awareness". Specifically, these concepts suggest that the priority of the collective interest against the individual is not well-integrated in city communities.

Another barrier is the doubt about whether these spaces will be used (75% of agreement). This issue is not unanimously perceived by any type of actor; however, in each category, someone identifies this barrier. Future maintenance problems (46% of agreement) are also an important concern.

Consumers' lack of trust in the quality and health risks of producing food on rooftops represents the principal social barrier reported in some cities, including Bologna (Sanyé-Mengual et al., 2018a) and Berlin (Specht et al., 2016a; Specht et al., 2016b), as it is a new model of food production and there is an absence of information about how it performs in relation to air pollution in urban areas. This perception is related to prejudices and scepticism, which is one of the principals (lack of information and scope regarding UAGR) social barriers identified in this study. A recent study related to air pollution in rooftop crops shows that heavy metal concentrations in lettuce are less than the EU-legislated level even when the lettuce crops grown using open-air growing systems were located in high-traffic areas of Barcelona (Ercilla-Montserrat et al., 2018).

The previous studies identify low acceptance and concerns related to rooftop food production using soil-less growing systems, which is perceived as "artificial, unnatural, and not real" (Sanyé-Mengual et al., 2016; Specht & Sanyé-Mengual, 2017). However, this barrier was not mentioned in the results of the World Café. A positive perception was reported in a previous study in Barcelona (Ercilla-Montserrat et al., 2019). In this sense, it is important that Municipalities develop programs to disseminate appropriate information about UAGR crop systems and the quality of the products to the stakeholders, which could be reflected in the gradual decrease of this shared social barrier in various European cities.

In Berlin, a social perception was identified, namely that this type of project is exclusive and acts as a driver for gentrification (Specht, Siebert, et al., 2016). In NYC, noteworthy discrepancies in obtaining assets in the UA framework were noted, this generate inequality for UA projects (Cohen & Reynolds, 2015). Gentrification is also a concern and a paradox of urban greening (Cole et al., 2017; Specht & Sanyé-Mengual, 2017; Wolch et al., 2014). These perceptions were not mentioned in the World Café conducted in Barcelona. However, this study revealed a new concern about the lack of social cohesion; this social barrier was not found in previous studies where the social cohesion was perceived only as an opportunity.

Regarding social opportunities, several proposals were observed as well as numerous nuances when discussing the perceptions described under one opportunity topic. The only social opportunity that generates an absolute consensus in its perception among all the stakeholders was "social cohesion"; however, the relative weight of the responses was lower than that noted for barriers (16% of the total opinions versus 22%). In this sense, under the umbrella of the opportunity mentioned, the actors perceive that UAGR could offer the possibility to generate new rules and attitudes as well as the possibility of benefiting specific groups of users and offering new spaces for citizen participation at all levels (for example, geriatrics, schools, individuals, or families).

Another widely perceived opportunity (68% of stakeholders) corresponds to the possibility of creating community garden spaces, which was accepted by all participants related to the fields of research (RC) and private companies (PC). Educational opportunity emerges with the same percentage of perception although with a slight variation in the distribution among stakeholders. In this category, the richness and variety of references that we could classify as the same barrier were remarkable. It should also be noted that social cohesion was also perceived as a barrier (as lacking) and as an opportunity (as UAGR can offer new spaces and methods to generate it). Another important detail corresponds to the fact that many of the mentioned social barriers and opportunities are not "purely" social but are very interrelated among other categories (socio-economic, legal, administrative, and environmental).

Regarding social opportunities, this study and previous studies from Barcelona, Bologna and Berlin identified social cohesion and education as major benefits of the integration of UAGR projects (Cerón-Palma et al., 2012; Sanyé-Mengual, Anguelovski, et al., 2016; Specht, Siebert, et al., 2016). In this sense, UAGR emerged as a catalyst for community improvement and social interaction. In addition, UAGR the strengthened social ties and served as an educational tool and a major means of appreciating local products (Cerón-Palma et al., 2012). In discussing barriers and limitations, we found connections with the possibility of low user acceptance and social indifference; however, the lack of qualified personnel to take advantage of the educational potential, the incompatibility of UAGR with city activities, and the loss of rural jobs or social disparities about the accessibility to the production systems were not perceived as barriers in the World Café. Otherwise, the lack of information and scope of UAGR, which appear as the most important barriers in this study, are not reported in previous works.

Environmental barriers and opportunities

In the environmental field, less concordance is found among stakeholders compared with the social field. Thus, only one barrier, the Mediterranean climate, exhibits greater than 50% agreement among shareholder categories, and only two (Mediterranean climate and the uses and quality of water) generated consensus among all stakeholder categories.

Mediterranean climate obtains the specific weight of 30% with respect to total responses in this category, and it is identified by all stakeholders' categories. However, none of them identified it unanimously. Mediterranean climate is identified as a barrier regarding the form and frequency of precipitation, which occurs in sporadic but intense events (storms) with sun effects and wind. The uses and quality of water were also perceived as a barrier for all stakeholders although with less agreement and relative weight (29% and 16%). The barrier of lack of technical or/and environmental training exhibits the same percentage as the uses and quality of water. This limitation refers to the lack of knowledge by the stakeholders involved in UAGR projects in various relevant topics, including bird migration and the selection of vegetation or species that should be introduced to preserve ecosystem equilibrium. However, this barrier was not identified by any of the actors corresponding to the owners and users (OU) category.

The major environmental barrier identified in the World Café was Barcelona's climate conditions. This result had no relationship between the environmental barriers reported in the previous works (e.g., Cerón-Palma et al., 2012; Sanyé-Mengual et al., 2016; Specht et al., 2014), which could be attributed the participants in this study who interpreted the environmental concept in relation to the climate and natural resource conditions for growing food rather than environmental impacts. The major environmental concerns in the previous research were related to the environmental impact of construction materials (Sanyé-Mengual, Anguelovski, et al., 2016; Specht, Siebert, et al., 2016; Specht & Sanyé-Mengual, 2017). Health risks due to air pollution, low expected quality products (Specht, Siebert, et al., 2016), and problems regarding organic waste management (Cerón-Palma et al., 2012) were not mentioned in the World Café.

With respect to opportunities, the heterogeneous tendency remains, and no clear opportunity was perceived in four of five categories by participants. The category with the greatest percentage of acceptance (improved life quality) does not reach 50%, and it has a relative weight of 16%. The next highest category of acceptance has a relative weight of 11% and 32% agreement. "Environmental education" was only perceived by stakeholders from public administration and private companies.

It should be noted that opportunities regarding climate change mitigation, reduction of UHI effect, energy savings, and improvements in thermal and acoustic insulation were very residual (none exceeds 7% relative weight).

In addition, carbon footprint reduction and reduction impacts associated with transport (Cerón-Palma et al., 2012) were identified under the improved air quality opportunity, as does biodiversity improvement (Williams et al., 2010). This is in keeping with the general perception that there is a clear lack of information about the scope and effects of UAGR within the population.

Regarding water management, policies from North Europe, required water retention capacity at list from 15 l/m^2 to 30 l/m^2 depending on the municipality to obtain a subsidy (Almelo, 2020; Amstelveen, 2019; Amsterdam, 2020; Den Bosch, 2020; Groningen, 2020; Hengelo, 2020; Leeuwarden, 2020; Leiden, 2020).

Legal/administrative barriers and opportunities

In terms of legal and administrative barriers and opportunities, more consensus was found among the stakeholders compared with the environmental field. Within the barriers, the lack of specific regulations and protocols regarding UAGR was remarkable with 71% of agreement among actors, 23% relative weight and unanimous identification by the four types of stakeholders. However, this barrier was only identified by all the individuals in the public administration group. Some interventions recorded during the World Café referred to criteria disparity, differences in legislation interpretation or lack of stability; these findings coincided with those reported by Specht, Siebert, et al., (2016) where stakeholders from Berlin perceived numerous uncertainties and regulatory gaps.

Another barrier that stands out is building volume limitation in the implementation of UAGR (54% agreement and 17% relative weight) as specific legislation is limiting in terms of structural reinforcement, shadow, or greenhouses facilities. Rooftop greenhouses encounter a barrier to development as some buildings are at or exceed their floor-to-area ratio (FAR) allowance, preventing an addition to the building. Policy changes to facilitate their development have been implemented in NYC where the Departments of Buildings and City Planning developed a waiver program for greenhouses seeking space on buildings that have met or exceeded their FAR (The New York City Council, 2010), and similar policy changes were recently implemented in Paris (Paris Local Urban Plan, 2018).

It is also important to mention two more barriers as they are also identified by all types of stakeholders although at a reduced percentage. First is the percentage of acceptance of the owners when implementing a UAGR in a community of owners. This is an important limiting factor given that approval by at least 80% of owners is required for a UAGR to prosper. However, for other modifications (such as the installation of an elevator, for example), 50% is sufficient. The second barrier refers to the difficulties of the legal commercialization of agricultural products grown on roofs or regarding urban agriculture. There is a clear identification of regulatory barriers for UAGR projects that is shared with other cities.

In the case of Barcelona, its General Metropolitan Plan does not allow agriculture activities inside the city, which makes the commercialization of food produced in the city unlawful. There are also height and volume limitations regarding the installation of RTGs due to the Spanish Technical Building Code.

Regarding opportunities, the feedback dynamics that are present in the previous categories are repeated. Specifically, barriers and opportunities were simultaneously identified. This does not mean that the barriers and opportunities coincide but rather that the actions to be taken to overcome them are focused on the same field as well as the opportunities that they present. In this sense, the possibility of developing specific regulations for UAGR (79% of agreement and 31% of specific weight) emerges as the most widely identified opportunity. Therefore, UAGR projects open the door to a deep analysis to elaborate upon their own regulations, unify the administration criteria and facilitate changes in the normative and legal procedures. It must be emphasized that all the stakeholders in the public administration group identified this opportunity, whereas no one in the research centres did.

As we have shown, regulatory barriers are potential opportunities to create laws and programs to promote and increase UAGR projects. The experience of cities that have changed policies concerning the integration of UAGR projects show the potential that Barcelona now must change the law towards regulations that are more *friendly* to UAGR projects. Thus, some legal initiatives have emerged in Barcelona. Beginning in 1999, the Ordinance of Urban Landscape of Barcelona authorized planters and pots on rooftops as long as they are mobile. Later, in 2013, the Barcelona Green Infrastructure and Biodiversity Plan advocated for the promotion of urban green zones on rooftops. In 2017, the Stimulus Programme for the City's Urban Green Infrastructures proposed an increase of 1 m^2 of urban green areas per inhabitant by 2030, taking rooftops into account. In 2018, within the framework of the Climate Plan 2018-2030 for Barcelona (the research of this paper is in fact part of this green infrastructure promotion plan by the city council), several proposals were introduced, such as laws to promote productive rooftops, boost the energy generation on rooftops and promote water collection and use in buildings. There is a need to assess the regulatory barriers of UAGR projects to encourage food production on rooftops within each city and explore the use of incentives to encourage these projects, providing advantages in the local economy and social benefits and mitigating environmental impacts.

Economic barriers and opportunities

The discussions of economic barriers are one of the sections in which there was less participation. Only 25 answers were registered (for 117 in social barriers or 74 in legal barriers), and no barrier reached 50% agreement among stakeholders.

Taking this lack of engagement into account, the most widely perceived barrier corresponds to the initial capital investment with 46% agreement among stakeholders but a relative weight of 40%. This barrier was identified by all the typologies of participants. This barrier refers to the installation and facilities costs, work, and materials, as well as economic disproportion between the necessary structural reinforcement and the cost of the UAGR elements. In addition, the rehabilitation of a roof under a UAGR project can be much more expensive than conventional rehabilitation. Stakeholders from this and other worldwide (Barcelona, Berlin, Chicago, Illinois, and Hong Kong) studies expressed their concerns about the financial issues of UAGR perceiving higher investments (Hendricks & Calkins, 2006; Sanyé-Mengual, Anguelovski, et al., 2016; Specht, Siebert, et al., 2016; X. Zhang et al., 2012).

Other significant barriers include maintenance costs (not identified by owners and users) and the low perception of UAGR's benefits and advantages given that these factors are perceived as "extra expenses", and there is minimal interest in investing in it. These findings coincide with other studies where maintenance costs have been ranked by housing project managers as the third most significant barrier in Hong Kong, the third decision priority by owners and architects from Chicago and Indianapolis, and one of the most significant barriers identified by Chicago's architects (Hendricks & Calkins, 2006; X. Zhang et al., 2012). Weak structural loading for integrating UAGR systems as well as increases in design and construction cost were also reported by Zhang et al., (2012).

Regarding this fact, the relationships between this barrier and the social barrier of a lack of information and prejudices regarding UAGR emerged since users are not aware of the potential benefits that the implementation of such a project can bring, including economic benefits in the form of savings, for example, in energy bills or the development of activities and services on the roofs.

The difficulty of commercializing the products obtained from UAGR appeared in a residual manner during the World Café (4% relative weight).

Previous studies from Barcelona, Berlin and Bologna (Cerón-Palma et al., 2012; Sanyé-Mengual et al., 2016; Sanyé-Mengual et al., 2018a; Specht & Sanyé-Mengual, 2017) also identified minimal or no perceived economic benefits as a strong barrier together with the fact that it is difficult to develop a rooftop business (connected with legal issues), which some authors (A. Palmer et al., 2016; Specht & Sanyé-Mengual, 2017) have also identified as a prominent economic barrier together with the competition of UAGR with other rooftop uses.

In terms of opportunities, the profits derived from the new uses of the roofs clearly stands out to profit economically from a space that was previously not associated with any pecuniary use. This opportunity stands out above the others with 67% agreement among stakeholders, 32% relative weight and identification by all types of actors. Within a "direct profit" perspective, a multitude of business opportunities is found for the community and/or construction companies that incorporate UAGR with possibilities, such as renting the space, guided tours or holding events, potential food and rainwater harvesting, renewable energy production/self-consumption and the production and possible sale of resources. The reduction of costs related to food production, consumption, and distribution; savings in energy bills; and the switch of the production chain to a more local scale represent indirect opportunities identified in the World Café.

Other highlighted opportunities in terms of the percentage of agreement and relative weight include the added value for the building (revaluation), the possibility of creation of new companies and jobs or the commercialization of local products and/or services. However, for all these opportunities, the perception among the stakeholders is very heterogeneous. Participants in the field of public administration (PA) and private companies (PC) are very receptive, whereas those involved in research centres (RC) or owners and users (OU) are less receptive.

When discussing economic opportunities, it is important to note the double-stranded character presented by the participants. In this sense, employment opportunities cannot imply a significant number of liveable wage jobs, and they even require additional expertise. Furthermore, the increased value added to the buildings can lead to the displacement of low-income residents.

Short-term business opportunities may imply unproven profitability in the long-term along with indispensable financial and political support, which is not always assured (A. Palmer et al., 2016). The economic feasibility of these projects must be assessed on a case-by-case basis (Freisinger et al., 2015).

Technological and architectural barriers and opportunities

Two architectural and technological barriers stand out. First, the previous situation of the elements on the roof was identified as a barrier with 62% agreement among stakeholders and 23% relative weight. This barrier refers to the current uses and pre-existing elements in the roof that constrain adaptation for new UAGR uses, such as air conditioning facilities, TV aerials, photovoltaic panels, or gardening elements. The second barrier, which is interrelated with the legal field, is the building's load limitation with 58% agreement and 22% relative weight. Both barriers were identified by all the typologies of the stakeholders but not unanimously.

The complexity of incorporating food, rainwater harvesting, and renewable energy system flows in buildings; the transportation of inputs and outputs of UAGR systems; complications in terms of rehabilitating existing roofs or the use of polluting construction materials are rarely mentioned in the World Café. Collectively, these barriers have less than 10% relative weight.

The third perceived barrier (UAGR accessibility) is not often reported in the literature but issues associated with this barrier are extensively studied in the literature (Cerón-Palma et al., 2012; Nadal, Cerón-Palma, et al., 2018; Sanyé-Mengual, Anguelovski, et al., 2016). Along with these issues, the risks associated with urban integration, which include conflicts (Specht, Siebert, et al., 2016; Specht & Sanyé-Mengual, 2017) with the "urbanity" and "agriculture" concepts, animal production, noise and/or smell problems or visual/aesthetic image conflicts, were not mentioned in the World Café; however, the possibility of aesthetic city improvement was perceived as an opportunity. Load resistance was identified in this and previous studies from Barcelona (Cerón-Palma et al., 2012). Although the previous literature has referred to large barriers and opportunities for social, economic, and environmental issues, the clear identification of architectural barriers and opportunities is lacking. In this sense, this study may make an important contribution to this specific issue.

Regarding opportunities, it is remarkable that none are identified by all types of stakeholders. This notion is reflected in the low percentages of agreement among actors. Thus, no opportunity reaches 50% agreement, and the highest percentage is 31%. Thus, the most perceived opportunity (with 32% agreement and 15% relative weight) corresponds to the possibilities of aesthetic improvement offered by UAGR project implementation, including the development of architects' creativity, developing new "beauty" and "urbanity" concepts within the city or the possibility of "hiding" pre-existing facilities/machinery on the roofs. However, this opportunity was only identified by the actors belonging to public administration and private companies.

New space uses and the possibility to update current installations were perceived with similar agreement and relative weight (26% and 12%, respectively). In addition, although the numbers are lower than those noted in the first mentioned opportunity, their acceptance among the types of actors is extensive given that only stakeholders belonging to research centres do not identify them. The new uses of space include the possibility of creating quality and comfortable areas, the use of underutilized spaces or responding to new spatial needs. Further, the possibility of updating current installations includes the detection and amendment of hidden deficiencies as well as improvement in the current state of the roofs.

The relationship between architectural/technological and environmental opportunities is also noteworthy as many proposals in the architectural field have a direct impact on the environment. In this sense, for example, the opportunities to cities and buildings that are more sustainable, such as improvements to thermal and energy insulation or the possibility of creating green corridors, were identified in both categories. Special mention should be given to the "construction" stage, which only presents four technological/architectural barriers and one barrier regarding legal/administrative issues, and no opportunities of any type were identified.

7.3.2 Barriers and opportunities scale: building, city or global

Figure 7.4 illustrates the results related to scale. The overall results showed that the barriers and opportunities identified by stakeholders during the World Café were mainly distributed between "city" (47%) and "building" (44%), whereas "global" remains at 9%. Regarding barriers, the data from the World Café reflect that 45% belong to "city", 46% to "building" and 9% to "global".

In terms of categories, "city" is the predominant scale in the legal and administrative barriers (approximately 70% of relative weight), whereas the "building" scale (75% of relative weight) is emphasized in the architectural and technological barriers. The remaining present a more homogenous distribution with percentages of approximately 50% between "city" and "building". The "global" scale has minimal impact on the barriers, reaching only 8% relative weight.

With regard to opportunities, the "building" scale is still outstanding (close to 70% of relative weight) in the technological and architectural field, whereas the "city" scale stands out with 63% relative weight in the legal and administration area. In the economic field, the distribution is homogenous with approximately 45% of opportunities pertaining to the "city" scale and 36% to the "building" scale. In the environmental field, the opportunities are distributed homogenously between the "building" and "city" scales (with relative weights of 46%, respectively).

Finally, in the social sphere, more opportunities appear is the "city" scale at approximately 55% followed by the "building" (35%) and "global" (10%) scales. However, the "global" scale minimally represents 10% of the total perceived opportunities. Additionally, the "city" scale encompasses 49% of opportunities, whereas the "building" scale occupies the remaining 41%.

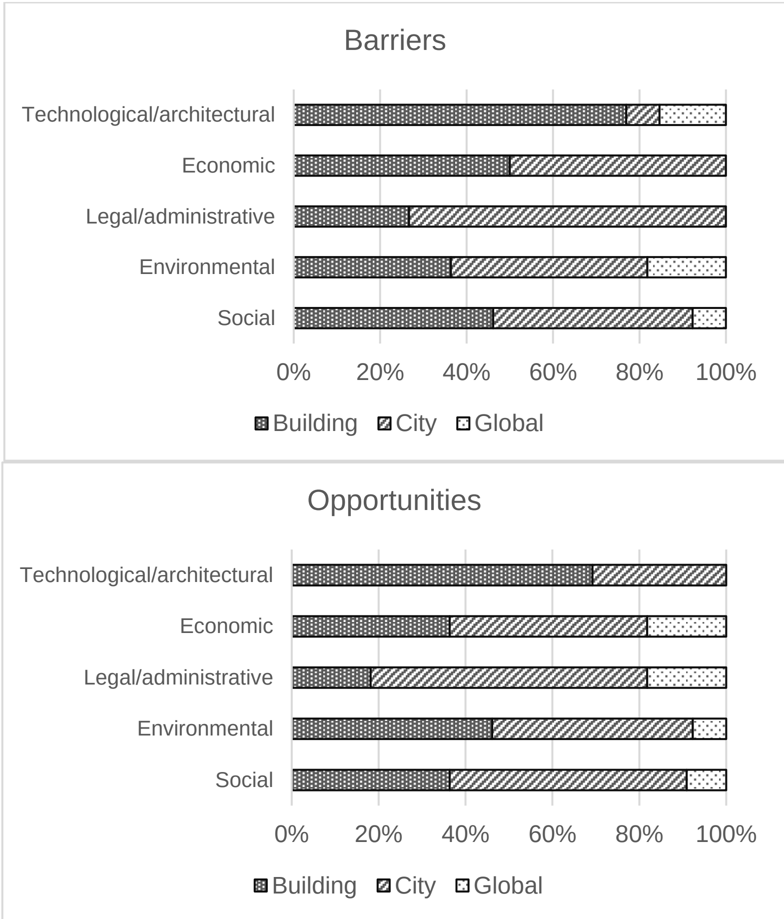

Figure 7.4. Scale of impact of potential barriers and opportunities regarding UAGRs in the city of Barcelona.

7.3.3 Barriers and opportunities within UAGR projects life cycle stages

Regarding the stages of a UAGR life cycle, it is essential to highlight the clear division between barriers and opportunities (Figure 7.5). Referring to the barriers, the "project" stage stands out compared with the remaining stages (62% relative weight). Next, we find the "use" stage (29%) followed by the "construction" stage (9%). Thus, only the environmental category presents a predominance of the "use" stage in the discussions of the barriers, whereas barriers in the other categories (technological/architectural, legal, economic, and social) are clearly project based.

Within the opportunities, the distribution changes radically, and a clear predominance of the "use" stage emerges with 84% relative weight of the total of opportunities. The "project" stage presents 16% relative weight, whereas no opportunity is identified at the "construction" stage.

Thus, until UAGRs are in operation, most opportunities are not perceived (or they simply do not appear until the UAGR is completely operational). This finding leads us to consider why it is difficult to perceive UAGRs' benefits given that without any or fewer UAGR projects in operation, the population will never be aware of its implications and advantages.

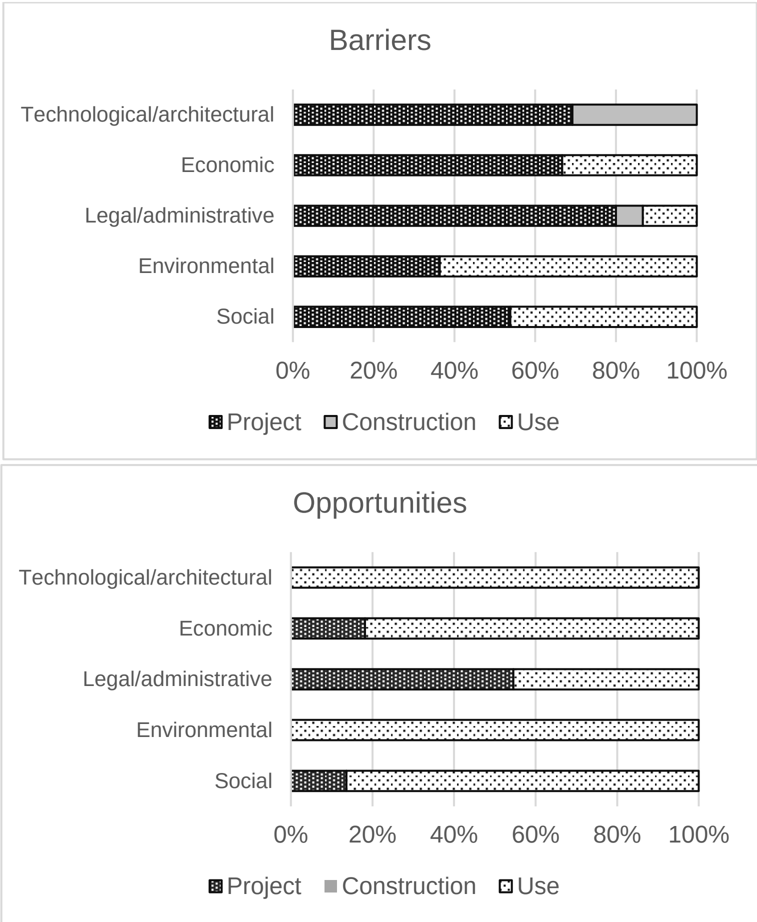

Figure 7.5. Stage of UAGR life cycle where potential barriers and opportunities emerge regarding UAGRs in the city of Barcelona.

7.4 Takeaway for practice

Policies for integrating UAGR projects should be an interlinked system of laws on national, regional, and local levels and connected with legal regulations regarding construction, resource management, commercial, and urban planning. Based on the results of this work, some practice and policy recommendation are described:

1) Planning authorities must consider UAGR projects in their national and local plans to encourage UAGR on new buildings and achieve UAGR projects through new policies and modifications in urban and building codes by considering the particularities of local development plans.

2) For existing buildings, it is generally more difficult to integrate UAGR according to buildings preconditions. In this case, the integration of incentives should be flexible, and several options must be developed, for example tax reduction subsidies or call for projects with financial support. An example of such incentive is determining the subsidy amount per each constructed square meter or a percentage of the total

construction costs. It is important to create a simple structure of the offered incentives and clearly establishing what the project should encompass and the minimum requirements to be eligible to apply.

3) For the practice of food production on rooftops, the following legal issues must be addressed:

- A flexible land-use that allow agricultural activities in cities must be considered by urban planners.

- Trade of products must be allowed with accurate production and distribution regulations.

- In the case of RTGs, it is necessary to develop a more comprehensive law to allow this type of infrastructure. Regarding the volume and floor area permitted in building codes and restrictions for building heights regulations should be flexible to support rather than act as a barrier.

4) Financial incentives should not be assigned exclusively to the stage of UAGR construction. The stage of use is extremely important. However, it requires maintenance works, and a subsidy plans for maintenance costs should be considered.

5) Policies also can encourage other environmental goals through UAGR projects. A minimum requirement and a type of score ranking can be developed to offer more subsidies or incentives according to the solutions integrated in the projects regarding goals in specific locations or circumstances, for example:

- Stormwater runoff mitigation by water retention capacity.

- Rainwater use by collecting rainwater from rooftops.

- Integration of renewable energy by including photovoltaics, solar thermal panels, or wind turbines.

- Social cohesion by including spaces designed to create community activities.

6) To improve education and awareness of UARG functions and benefits, the following practice are recommended:

- Education programs to disseminate appropriate information to residents, investors, and city policy makers should be integrated in a municipal campaign in collaboration with academics, research centres, or specialized companies involved in UAGR projects.

- Those who are interested in learning more about the technology should have access to UARG demonstration projects.

- A database of UAGR projects in cities and scientific evidence regarding benefits of UAGR projects should be generated.

7) Regarding the development of technology and training programs, it is important to create policies to encourage the development of technologies regarding sustainable

criteria, such as materials and processes for integrating UAGR projects. Also, it is necessary to support training policies for professionals specialized in sustainability regarding UAGR design and construction.

8) The development of UAGR projects could cause gentrification. In this sense, it is important that government integrates regulations to avoid it.

7.5 Conclusions

This study has allowed for the attainment of a highly instructive picture of the perception of UAGR projects in the city of Barcelona, and this information can aid in the characterization of other cities with similar features.

Because most barriers are perceived in the project stage and opportunities are not perceived until the use phase, an effort by the government is needed to implement UAGR projects such that the population can perceive the benefits generated in all areas of society in an accurate manner.

This study highlighted the need for awareness and information activities, and these barriers can be solved with targeted information, education, and research dissemination of knowledge regarding UAGRS projects benefits among different actors but especially owners and users to promote a better understanding of their potential benefits. To elaborate a clear specific regulation regarding UAGR, generating more social consensus and cohesion along with economic support for those projects will be critical in facilitating its implementation. Moreover, despite the extensive list of barriers and opportunities, their relative weights are concentrated, exhibiting minimal dispersion. These features would facilitate a policy approach in Barcelona. Results can be a reference to others Mediterranean and compact cities aiming to boost agri-green roofs since they share similar characteristics such as urban forms and buildings, and similar issues such as lack of information and specific regulations and protocols, social cohesion, and initial investments in this type of facilities, among other factors. Therefore, this research is an asset towards helping such type of cities to predict and overcome plausible limitations and promoting the opportunities yielded by these projects.

Considering the focus for future research, it would be appropriate to investigate the development of indicators to monitor the impact of UAGR to verify how they match the stakeholders' perception. A constraint for our study was not having enough data to perform a comprehensive sustainability assessment since agri-green roofs are recent infrastructures and the most critical point was to identify all possible limitations and opportunities regarding agri-green roofs in Barcelona, intending to transform these projects in long-term successes and help other cities in possible drawbacks they can find to implement them in their cities. For these reasons, for future studies, we recommend carrying out a sustainability assessment regarding agri-green roofs.

It would also be appropriate to generate more consensus and social cohesion. One essential means of contributing to this purpose would be to expand dissemination studies on UAGR opportunities and to respond to the main prejudices of potential users. Research to quantify the economic, environmental, and performance benefits of UAGR will ultimately generate interest in potential adopters on the value of this project. The key points that should be evaluated in future work include the following: methods to introduce UAGR within current legal frameworks and expand on the interest in the impact and sustainability of the used materials and the disequilibrium that can be generated in local ecosystems.

Policies regarding development of technology and construction for more sustainable buildings as well as educational programs to train professionals in the field of sustainable constructions are important to address.

Several of the identified barriers have close links to government policy insufficiency; thus, there is urgency for policy instruments. Support policies should include various financial opportunities as well as bylaw requirements, and municipalities should provide technological information and support for UAGR systems in the construction phase and consider incentives for the use stage.

Part V

Discussion, conclusions, and further research

Chapter 8

Discussion of main contributions

CHAPTER 8 - Discussion of main contributions

This chapter discusses the main contributions of this thesis and their implication for cities, Figure 8.1 summarizes the main contributions briefly described in the following sections organized according to the sequence of the chapters. The contributions support the development of future studies.

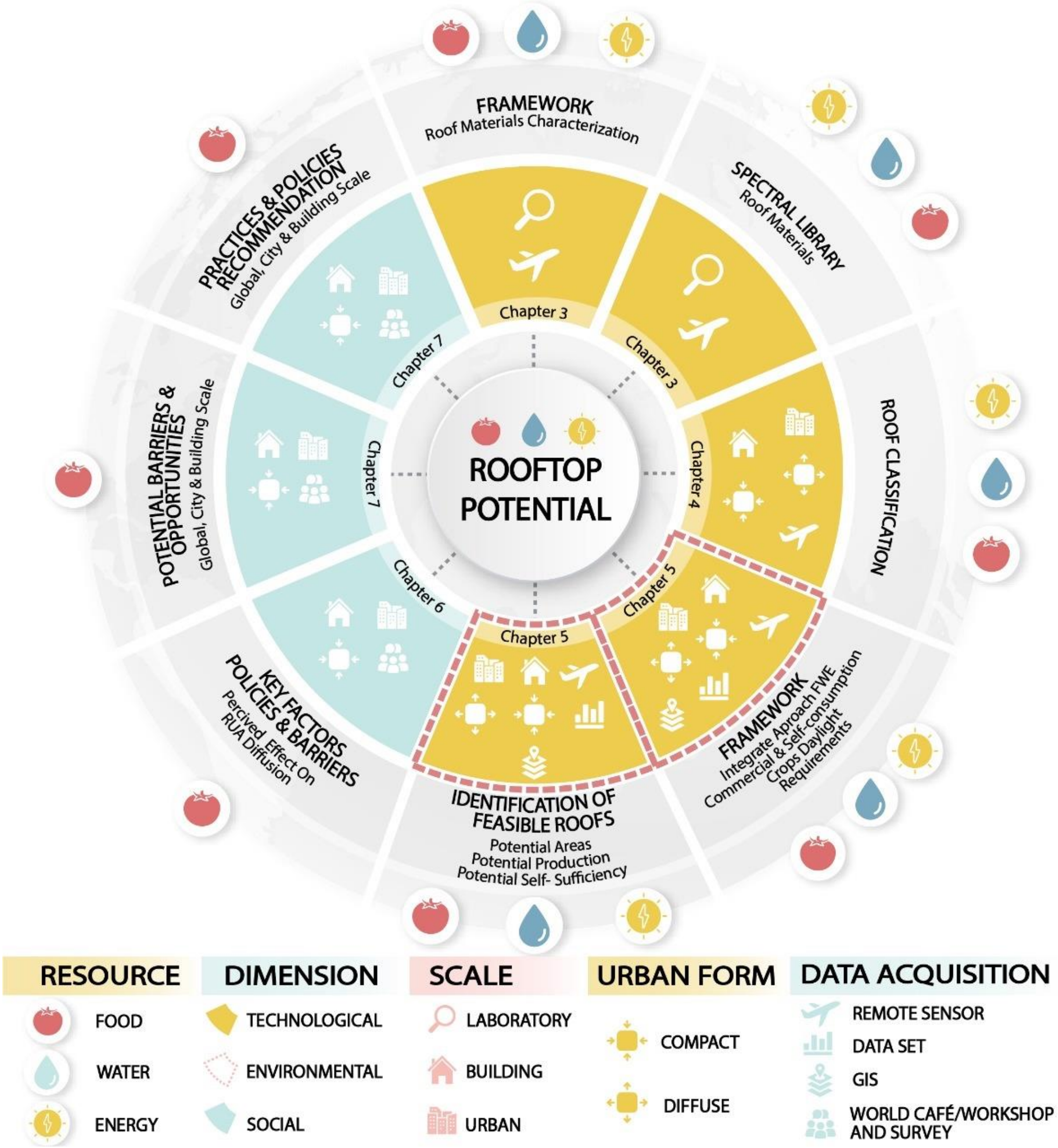

Figure 8.1. Summary of contributions of this thesis.

8.1 Laboratory-based approach for identifying roof materials

This thesis proposes a laboratory-based methodological scheme. The use of high-spatial-resolution sensors (used for airborne surveys) for spectral data acquisition of roofs in the laboratory is a novelty. In addition, this thesis contributes to automation in the raw data processing stage and obtaining spectral signatures through the development of a script.

This dissertation contributes to the knowledge of the spectral characteristics of roof materials compiled in a spectral library. Differences in some ceramics; fiber cement and concrete; metals, and some plastics were identified (see Figure 8.2). Ceramics exhibited strong absorption in the visible region. The spectral signature of the fibre cement and concrete class showed a reflectance increase up to approximately 600 nm. Metal showed increasing reflectance peaks at approximately 450 nm and absorption reflectance peaks at 500 nm.

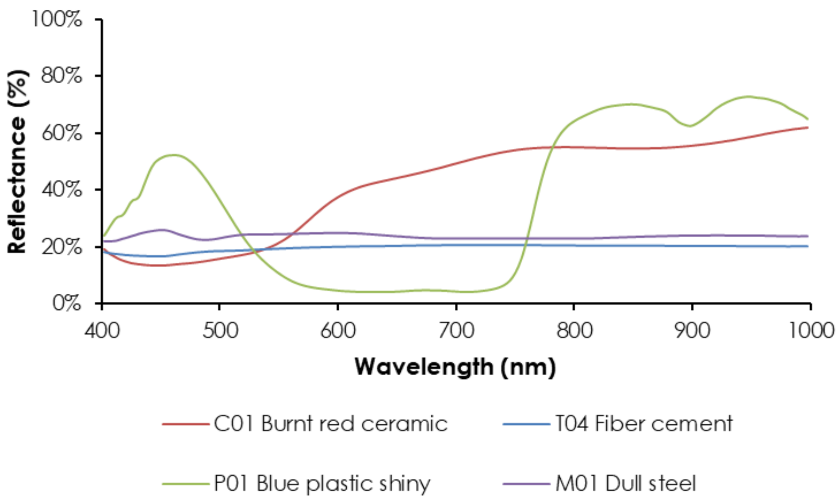

Figure 8.2 Spectral reflectance of different roof materials.

One of the main findings was low spectral separability within materials from the same class and between materials of a different class. Especially for dark plastics, gravels, and grey concrete tile roofs. This study demonstrates that VIS-NIR spectral reflectance data might not be spectrally distinct enough to distinguish and map materials with similar finishing colors.

Spectral variability in plastic samples for visible wavelengths was identified. The spectral signatures of plastics were similar to paint samples due to the similar finishing color.

A relevant finding concerns metals material. These materials showed similar flat spectral signatures and low reflectance values, especially in the NIR region.

8.2 Roof classification in cities

The most relevant contribution is the identification of different roofing classes by means of remote sensors until now non-existent in the study area. In addition, it is the first study focused on mapping roofs with the perspective of FWE roof production applications.

The present thesis used two RS simultaneously with different spectral ranges VIS-NIR and TIR. It was identified that TIR information allowed to discriminate material classes with similar color finishing that present the same spectral shape in the VIS-NIR spectral range (see Figure 8.3 and Figure 8.4).

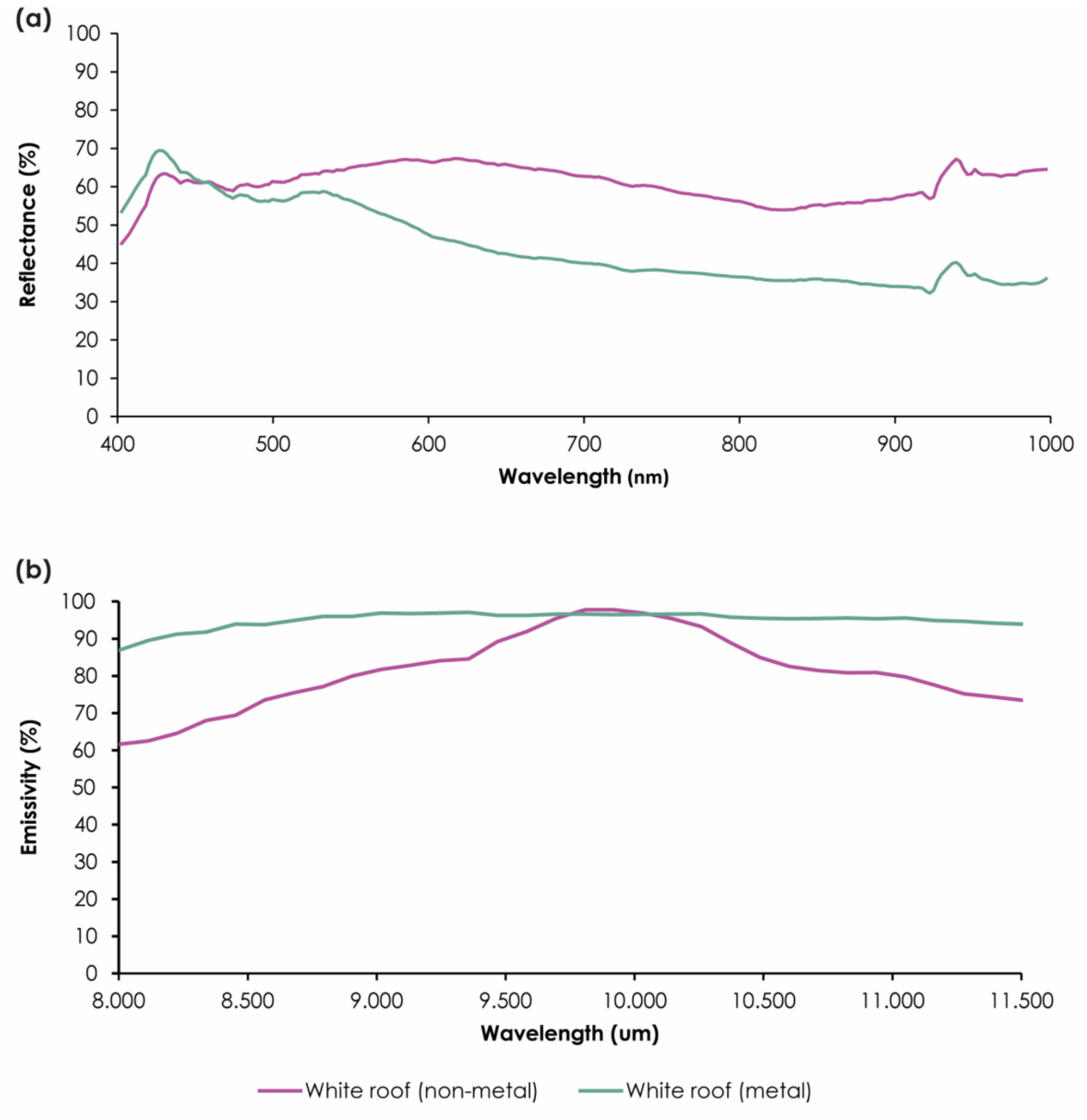

Figure 8.3 Spectral signatures of white roof classes. (a) VIS-NIR (b) TIR spectral ranges.

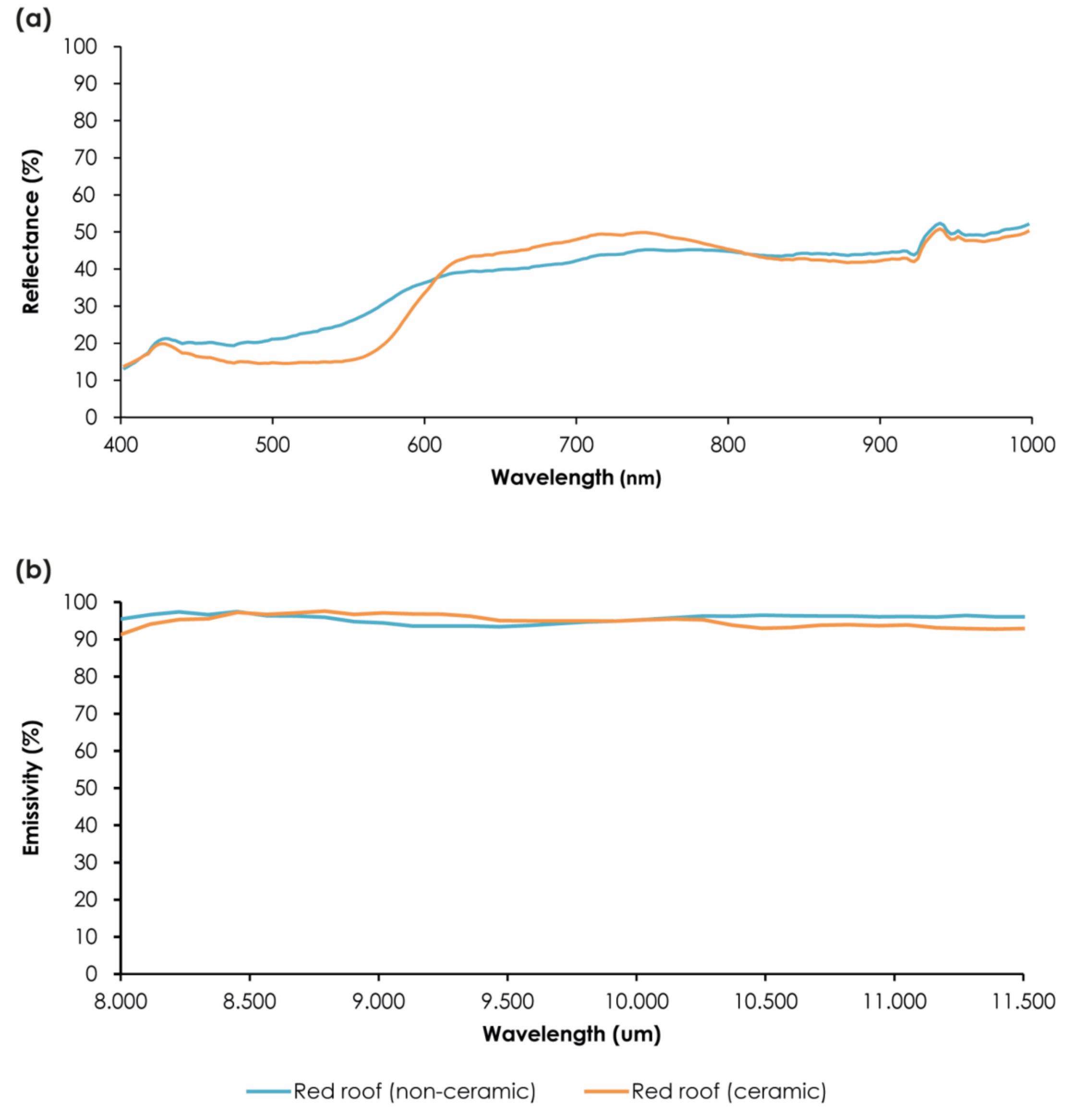

Figure 8.4 Spectral signatures of red roof classes. (a) VIS-NIR (b) TIR spectral ranges.

Unsupervised classification is reliable to classify roof materials in urban contexts without prior data. An important contribution is the verification process carried in this thesis to validate roof classification which was developed using three different approaches: visual inspection, information from field experts, and field inspection. Also, it was demonstrated that the size of roofs did not influence the accuracy of classification. A highlighted finding is the existence of elements on rooftops (such treetops or air conditioning facilities) and errors which decrease accuracy classification.

8.3 Assessment of roofs suitability for integrating food-water-energy systems

One of the main contributions is the development of a framework to identify feasible roofs for the integration of food, water, and energy systems using RS technology as the main tool for data collection and the identification of and inclusion of multicriteria sets.

The contributions regarding the criteria included in the framework are the definition of lighting criteria requirements for different crops, this allowed to include, rather than discard, rooftops that could also be productive even with low average solar radiation; the inclusion of different purposes for RUA commercial and self-consumption and the integration of the use of the building.

Another contribution is the framework application, thus, the identification of feasible roofs for integrating FEW systems. It was identified that 83% of the roofs are feasible to integrate one or more systems. Eight percent of the roofs are feasible for integrating RUA and RWHS, 50% for PV and RWHS, and 42% for RWHS.

It was identified that services and housing roofs were the most suitable for integrating RUA. Industrial rooftops were less suitable even when were present in a larger proportion compared to roof services. About housing buildings, it was found that blocks or towers configured from an isolated multifamily building are the best-suited typologies for RUA purposes. Lower feasibility was identified for compact and open building blocks, detached and terraced houses, these typologies showed many shadows and pronounced slopes.

It was found that the use of airborne datasets provided by different institutions and acquiring data on different dates generate some outdated data. However, the information not found was minimal (1.5%).

Self-sufficiency analysis for crop irrigation showed that the integration of RWHS could supply 94.3% of the total water requirements for lettuce crops in open-air systems and 82.1% for the same crop in RTGs, as well as 63.2% for tomatoes in open-air and 53.0% for the same crop in RTGs. The present thesis showed that feasible roofs for RWHS could meet 44% of household demands. Potential areas for PV could meet energy self-sufficiency of 18%.

8.4 Legal constraints and opportunities for rooftop agriculture in European cities

This thesis proposes a framework with two approaches a workshop and a survey based on the Likert scale for identifying potential key factors, policies, and barriers associated with the integrations of RUA from stakeholder's perceptions. A contribution is the key factors (12), context factors (13), policies (11), and barriers (25) used to develop the survey. This section of the thesis also contributes by providing an overview of promoting factors and legal constraints for integrating RUA in different EU cities, Barcelona, Berlin, Bologna, and Paris.

It was identified education, environmental, research, technological innovation, food production, and social cohesion as relevant factors for integrating RUA. Productive spaces, cultural values, social cohesion, social rural-urban links, high cost of urban land are contextual factors that promote RUA. Major context factors which constraints RUA are the cost of water and pollution. Policies related to food trade and urban planning limited RUA integration. Most barriers relate to the limits of building heights, historical buildings, a lack of specific building codes, building design, roof accessibility, high cost of infrastructure, and policies that prohibit RUA product sales were identified.

After a global analysis of several European cities, a detailed study of the barriers and opportunities in one of these cities, Barcelona, has been carried out.

8.5 Perceptions on barriers and opportunities for integrating urban agri-green roofs: a European Mediterranean compact city case

The thesis contributes to the knowledge of potential barriers and opportunities in the framework of a real case study the Barcelona's First Green Roof Contest. A relevant contribution is the integration of new perspectives regarding the identification of barriers and opportunities according to the life cycle of UAGR and the scale where they are presented.

Thus, this thesis provides information about barriers and opportunities in the life cycle and scale. In addition, the use of the World Café method with no presence in the field of study.

Most of the barriers appear during the project stage. Most opportunities are perceived in the stage of infrastructure use. Building and city are the scales where most of the barriers and opportunities appear. Legal and administrative barriers emerged at the city scale and architectural and technological at building scale.

In this study, some barriers were identified as being more prevalent than in the previous study. These barriers are the lack of information and social cohesion regarding UAGR projects; and the Mediterranean climate. The lack of specific regulations and protocols; the initial investment; and the pre-condition of the roof and its load-bearing capacity were identified as major barriers in both this and the previous study. On the other hand, social cohesion; improved life quality; new specific regulations; the profits derived from UAGR projects; and aesthetic improvement were identified as main opportunities.

A relevant contribution of this section of this thesis is the practices and policies recommendations for food production on rooftops. They are summarized in the following topics: urban planning, architectural, especially existing buildings, legal (land-use, trade of products, building codes), financial incentives, environmental goals, education and awareness, and development of technology and training programs.

Chapter 9

Conclusions of main contributions

CHAPTER 9 - Conclusions of main contributions

This chapter summarizes the general conclusion of the thesis based on the research questions defined in Chapter 1. Each of the four questions responded to specific chapter, questions are organized following the order of the chapters.

Addressing research questions

This section addresses the four specific research questions set out in chapter 1 of this thesis.

Question 1

What are the steps to acquire spectral data from roof materials at laboratory-scale and what are the spectral characteristics of these materials?

Roof materials can be identified by spectral signatures obtained with RS technology in the laboratory, this technology, and the methodology carried out, which included four phases:

6) Spectral data acquisition

7) Image preprocessing

8) Radiance data processing

9) Development of the spectral library

Spectral characteristics vary depending on the material. Flat spectral signatures were found for fiber cement, concrete, gravels and some metals, especially in the near infrared (NIR) spectral region.

Question 2

Are hyperspectral remote sensors a reliable tool to map roof materials in cities?

Hyperspectral remote sensors with the high-spatial-resolution are a useful tool for mapping roof materials without prior information. It is suitable to use two sensors simultaneously with different spectral ranges. The use of TIR data contributed to discriminate against some materials with similar spectral characteristics in the VIS-NIR spectral range.

Hyperspectral remote sensors represent relevant advantages compared to other methods used such as data collection with on-site visits. For example, saving time to obtain data and automated processes that can be applied at city scale for identifying roof materials.

Question 3

What approach is most suitable to identify and quantify the feasibility of rooftops to integrate urban agriculture (RTGs and open-air), rainwater harvesting, and solar energy systems in residential and non-residential urban areas?

An *automated* procedure based on RS for data acquisition and GIS tools allows identifying feasible roofs for urban agriculture, rainwater harvesting, and solar energy systems at the urban scale. The application of this approach suggests advantages such as a less time-consuming, *automated* process and the possibility to apply it at a city scale.

An approach that considered not only large areas for economic purposes in industrial, commercial, or retail buildings, but also other building use and smaller polygons for educational, social cohesion, and self-consumption purposes, allowed the integration of commercial and non-profit goals.

A method with special attention to solar access on roofs. Different ranges of light requirements are important for not excluding roofs that can be productive.

Question 4

Which are the key factors, legal constraints, barriers, opportunities and their perceived effect on RUA diffusion and in which scale and project's life cycle stage are presented?

Educational, environmental, research, technological innovation and food production are the most relevant key factor for integrating RUA. Perceived contextual factors that promote RUA are productive spaces revaluation, cultural values, social cohesion, social rural-urban links, and the high cost of urban land. Water cost and pollution are contextual factors perceived as limiting factors for the integration of urban agriculture.

Sustainability, financial incentives, development of new technologies, education, food production, the Milan urban food policy pact and Parisculteurs are policies that promote RUA. The most relevant policies that hinder RUA are food trade, urban planning, food production and architectural policies.

Most architectural barriers refer to RUA is prohibited in historical buildings, lack of a building code for RUA and the limits of building height.

Technical barriers are building design to operate RUA, difficulties of roof access, pre-condition of the roof and building structural load limitations.

Mainly economic barriers are the high cost of infrastructure, initial investment and policies that prohibit food sales.

Two social barriers are especially emphasized: lack of information and scope regarding these kinds of projects.

Technological and architectural barriers and opportunities were identified by stakeholders as building scale, legal and administrative as city scale, and economic, environmental, and social as building and city scales.

Most barriers are perceived in the project stage and opportunities are not perceived before to the use phase.

Chapter 10

Further research

CHAPTER 10 - Further research

This chapter describes further research lines considering aspects detected during the development period around the topics analysed in this thesis.

10.1 Remote sensing technology

Figure 10.1 summarizes further research which are described briefly in the following sections organized following the order of the chapters.

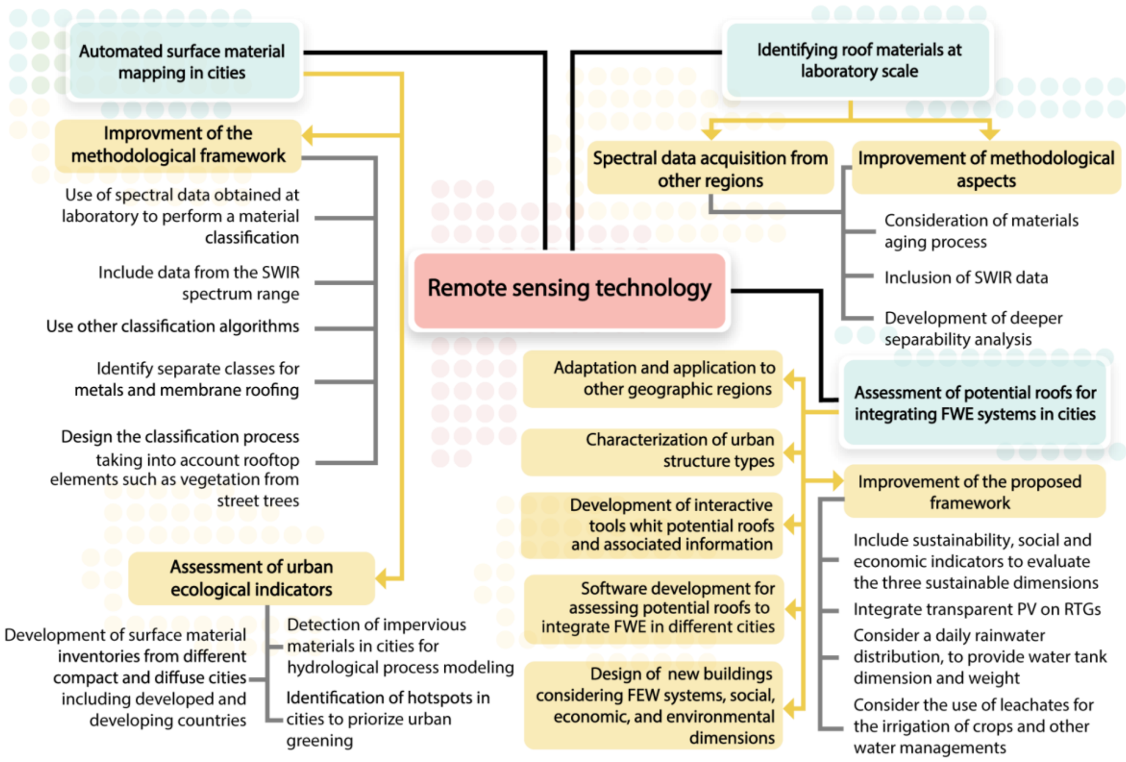

Figure 10.1. Further research lines and methodological suggestions for remote sensing technology.

10.1.1 Identifying roof materials at laboratory scale

Acquire spectral data of roof materials from different geographic context may be of interest considering the following methodological aspects:

- Consider the ageing process of the materials, as this may be a factor influencing the spectral data obtained.

- The use of TIR[5] and SWIR spectroscopy is best suited for several sets of minerals, clays, carbonates, sulfates, or silicates that are present on roof materials and could improve spectral separability.

- Develop a deeper separability analysis using other metrics, for example, B-distance.

[5] In this thesis, spectral data were collected with a TIR sensor (TASI-600). The data were processed and are graphically represented in Appendices 5.

10.1.2 Automated surface material mapping in cities

Methodological improvements and future research based on hyperspectral image data are described below.

1) Improvement the framework for mapping roof materials, the methods and tools from the present thesis can be the basis considering the following:

    - A typical practice for classifying materials is the use of spectral libraries, however, in the present thesis it was not possible to use them due to schedule time. Thus, it is recommended the use of spectral data obtained at laboratory to perform a material classification using hyperspectral data from high spatial resolution images acquired by airborne sensors or satellite platforms.

    - In addition to VIS-NIR and TIR include data from the SWIR spectrum range to improve classification results, since SWIR represents a larger dynamic range of reflectance values for some urban materials and is best suited for several sets of minerals, clays, carbonates, sulfates, or silicates that are present on roof materials, therefore, could improve spectral separability between materials.

    - Use other classification approaches such as supervised classification, for hyperspectral data and method classifiers such as Maximum Likelihood, Neural Network, Random Forest, Spectral Angle Mapper, or Support Vector Machine.

    - Identify separate classes for metals and membrane roofing among others due to the importance of the roof's load-bearing capacity by construction systems.

    - Identify existent PV on roofs and considered it in solar energy potential analysis.

    - Design the classification process considering rooftop elements such as vegetation from street trees and installations on roofs which negatively affect accuracy values.

2) Assessment of urban ecological indicators can be done based on surface material classification using hyperspectral image data from remote sensors

    - Development of surface material inventories from compact and diffuse cities including develop and developing countries, using automated remote sensing technology and GIS-based system, data can be applied in diverse urban planning sustainable works and can contribute for supporting environmental policies for cities.

    - Detection of impervious materials in cities has the potential to be used as input for the hydrological process modeling in urban areas and to propose different scenarios which can aid to support decision making process in urban planning as well as policies in cities.

    - Identification of hotspots in cities to prioritize urban greening (green roofs, rooftop urban agriculture) to mitigate urban heat island, the framework developed in this thesis can be the basis, nevertheless, some procedures and algorithms must be changed according to the main purpose.

o TIR remote sensing is a suitable tool to provide appropriate data for mapping hotspots.

o In addition to TIR remote sensor, it is recommended the use of SWIR image data information, aerial imagery, as well as the LiDAR data, to classify land cover into different land surface types.

10.1.3 Assessment of potential roofs for integrating FWE systems in cities

1) Improvement of the proposed framework.

   - Include sustainability parameters, develop a section for quantifying both environmental benefits and impacts during all the phases of life cycle FWE infrastructures.
   - In addition to ecological assessment develop social and economic indicators to evaluate the three sustainable dimensions.
   - Consider the use of leachates for the irrigation of crops and other water management.
   - Integrate transparent photovoltaic for allow food and energy production on RTGs.

2) Adapt and applicate the framework developed in this thesis to other geographic regions. For example, the establishment of the minimum roof area for commercial and non-profit purposes is necessary to examine and to develop for other locations, including both compact and diffuse cities from develop and developing countries.

3) Characterization of urban structure types due to urban morphology, the built environment, and building typologies affect the availability for integrating FWE systems.

   - Mapp materials from different urban structures based on remote sensing technology, using high spatial resolution hyperspectral image, LiDAR data, and GIS systems.
   - Perform a calculation of land cover indicators of urban structures such as building and vegetation density.
   - Quantify and analyze urban structure types in different cities for assessing the relationship between urban morphology and building typologies regarding FWE systems implementation.

4) Develop accessible information about potential roofs for stakeholder's decision-making process. Based on the results of this dissertation and future works applied in other case studies, the development of an interactive map where potential roofs can be consulted represents a helpful tool to stakeholders and decision-making for planning.

5) Software development for assessing potential roofs for integrating FWE in different cities can be a useful tool for stakeholders that are not necessarily researchers, this also could help in promoting productive roofs in cities.

6) Explore design for new buildings considering FWE systems, economic, social, and environmental dimensions as well as the integration of the flows.

10.2 Key factors, legal constraints, barriers and opportunities perception for integrating rooftop urban agriculture

Figure 10.2 summarizes further research lines and methodological suggestions for legal constraints, barriers, and opportunities for RUA integration, which are described briefly in the following sections.

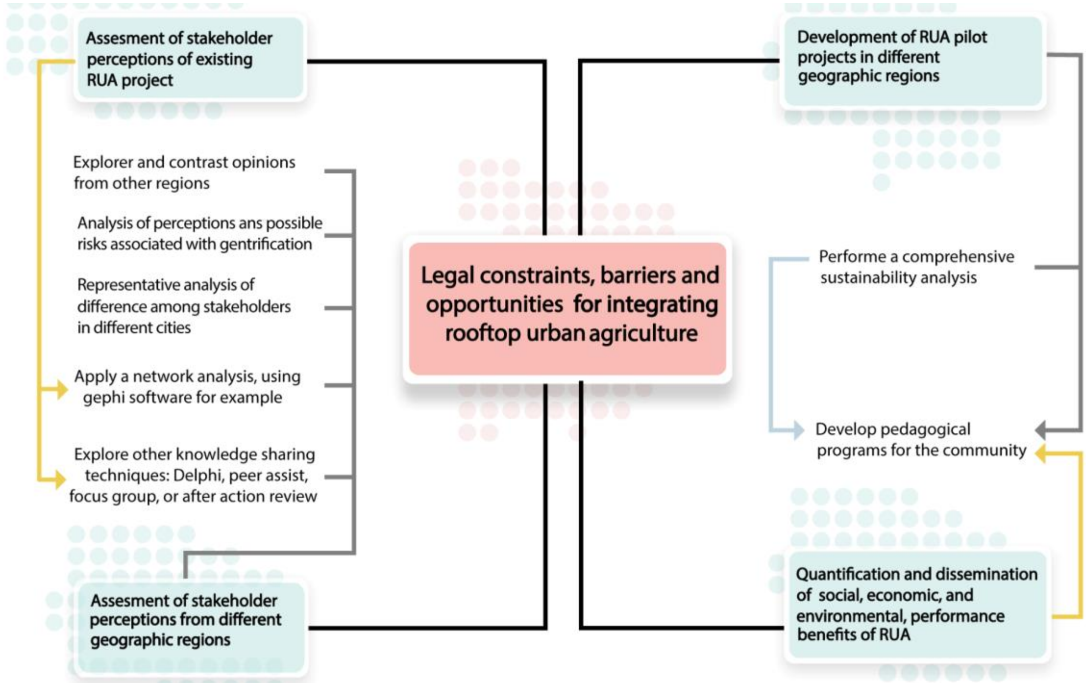

Figure 10.2. Further research lines and methodological suggestions for legal constraints, barriers, and opportunities for RUA integration

10.2.1 Development of RUA pilot projects in different geographic regions

- It is relevant to develop pilot projects in different cities considering the three dimensions of sustainability.
- Carry out comparative studies in different geographical areas, to see differences and similarities and to be able to develop the most appropriate model according to the specific needs of the area.

10.2.2 Quantification and dissemination of social economic and environmental performance benefits of RUA

- It is important to demonstrate sustainability about RUA, quantify the social, economic, and environmental impacts of RUA.
- Include social and educational purposes, develop pedagogical programs for the community.
- Design appropriate communication strategies to disseminate information and the benefits of these infrastructures.

10.2.3 Assessment of stakeholder's perceptions from different geographic regions

- Climatic conditions from other locations are suitable for RUA which has been little explorer, for example, in Latin American cities. The work developed in this thesis can be used as a basis however, some methodological improvements are necessary.

    - Participants, it is important to have a representative sample and similar proportion of stakeholders in the different areas that involve RUA as well as a similar proportion of participants by city study.

    - Perform a deep data analysis regarding differences between stakeholders from different cities, use a statistical analysis using U (Mann-Whitney-U-Test), x^2 (Chi"-Test) and r_s (Spearmen correlation) can be used for these purposes.

    - It can be useful to apply a network analysis which can be performed using gephi software.

    - Explore other knowledge sharing techniques, the workshop, survey, and World Café applied in the present thesis were useful for this study, however, other techniques can be explored such as Delphi, peer assist, focus group, or after-action review.

10.2.4 Assess stakeholders' perceptions of RUA already built projects

It is important to continue monitoring the perception of the stakeholders, especially those of Paris and Barcelona, which were the cities that at the beginning of the development of this thesis, initiated some policies to promote the development of RUA projects. Therefore, once the projects are built, it is important to contrast perceptions to detect social, environmental, economic, and legal barriers regarding projects already built. In addition, develop research using the knowledge sharing technique for example, *after-action* approach for learning and avoiding similar mistakes in future projects by determining what happened, why it occurred, and how to maintain strengths and overcome weaknesses. Conducting a study with a larger sample and exploring the hypotheses obtained in this thesis on the different perceptions among the different cities.

- Conduct a study related to the possible risks or existence of the gentrification phenomenon of RUA in cities.

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Appendix 1. Supporting information for chapter 3

Laboratory-based spectral data acquisition of roof materials

Supporting information 1.1. Script developed for processing the radiance data

```
#################################################################################
#################################################################################

class sampleToAnalyzeAISA(object):
    def __init__(self, angRanges,lin2Wav,lin2Ang,lin2Spec,ID,imgFile,sampleMaskFile,refMaskFile,QCpath):

        # Maps parameters
        self.angleRanges  = angRanges # Angular ranges for spectra to be computed
        self.lineToWave   = lin2Wav   # Relationship between image band coordinate and Wavelength value [nm]
        self.lineToAngle  = lin2Ang   # Relationship between image pixel coordinate and incidence angle [º]
        self.lineToSpec   = lin2Spec  # Spectralon(R) spectral response
        # Retrieve additional param
        self.nAngles      = len(self.angleRanges)
        self.nBands       = self.lineToWave.shape[0]
        self.sampleID     = ID
        # Read data & raster images
        self.sensImage    = gdal.Open(imgFile).ReadAsArray()          # Image to be processed
        self.sampMask     = gdal.Open(sampleMaskFile).ReadAsArray() # ROI defining the sample
        self.refMask      = gdal.Open(refMaskFile).ReadAsArray()       # ROI defining the reference (Spectralon (R))

    ############################################################################

    def getSampleSpectraForAllAngles(self):

        spectra         = np.zeros((self.nBands,self.nAngles),dtype=float)
         # Loop over angles
        for index,angleRange in enumerate(self.angleRanges):
            # Retrieve spectrum for a given angle
            spectrum =  getVNIRspectrum(self.sensImage,self.sampMask,self.refMask, self.lineToWave,self
            .lineToAngle,self.lineToSpec,angleRange)
            # Update spectral array
            spectra[:,index]   = spectrum
            return spectra

#################################################################################
def getVNIRspectrum(sensorImage,sampleMask,referenceMask,lineToWavelength,lineToAngle,lineToSpec,angleRange):
    # Get the angular mask (Pixels within the current angular range)
    angleMask              = computeAngularMask(lineToAngle,angleRange,sensorImage)
    # Get the multiband sample & reference arrays
    sample                 = sampleMask*angleMask*sensorImage
    reference              = referenceMask*angleMask*sensorImage
    # Perform the row (i.e., time) average
    sampleRowSum           = sample.sum(axis=1)
    referenceRowSum        = reference.sum(axis=1)

    maskSampleRowSum     = (sampleMask*angleMask).sum(axis=0)
    maskReferenceRowSum = (referenceMask*angleMask).sum(axis=0)

    sampleRowAvg           = sampleRowSum / maskSampleRowSum
    referenceRowAvg        = referenceRowSum / maskReferenceRowSum
    # Apply the calibration reference for the spectralone (externally provided)
    referenceRowAvg        = np.divide(referenceRowAvg,np.expand_dims(lineToSpec,axis=1))
    # Get the overlapping columns for both sample and reference
    validColsSample        = sampleRowAvg!=0
    validColsReference     = referenceRowAvg!=0
    validCols              = validColsSample*validColsReference
    # Get the corrected sample values
    correctedSample        = np.divide(validCols*sampleRowAvg.astype(float),validCols*referenceRowAvg.astype(float))
    validPoints            = np.isfinite(correctedSample).astype(int)
    # Get the column (i.e., angle) average
    correctedSampleColSum= np.nan_to_num(correctedSample).sum(axis=1)
    validPointsColSum      = validPoints.sum(axis=1)
    spectrum               = np.divide(correctedSampleColSum,validPointsColSum)

    return spectrum
```

Supporting information 1.2. Available number of pixels for each sample material

Material information		Number of pixels			
ID	Material	IFOV 1	IFOV 2	IFOV 3	IFOV 4
C01	Ceramic tiles	108287	171314	187541	161026
C02	Gres porcelain tiles	124781	167183	171161	162894
C03	Gres porcelain tiles	123133	161437	165128	147434
C04	Gres porcelain tiles	142740	191260	195810	179309
C05	Gres porcelain tiles	116428	155965	156241	162027
T01	Concrete tiles	52860	75027	48649	2864
T02	Concrete tiles	84130	139138	183301	203680
T03	Concrete bricks	58675	78583	80464	0
T04	Corrugated fibre cement shingles	156623	209835	214856	223893
M01	Steel shingles	86148	115410	118179	123145
M02	Galvanized steel shingles	88333	118341	121193	112239
M03	Inox steel shingles	80808	108262	110852	40147
M04	Aluminium shingles	82680	110770	113420	36042
M05	Steel shingles with paint	46344	62032	63526	65516
M06	Copper shingles	81676	109412	112029	102333
M07	Zinc shingles	81432	109098	111708	17220
M08	Steel with paint (sandwich panels)	70310	94155	96407	71841
M09	Aluminium with paint (sandwich panels)	67651	90602	92769	88533
PT01	Shingles with blue paint	98991	132579	135783	122037
PT02	Shingles with red paint	96080	140407	148262	128012

P01	Methacrylate shingles	88059	117910	120803	67937
P02	Methacrylate shingles	85956	115160	114316	30311
P03	Methacrylate shingles	85488	114532	115311	39840
P04	PVC shingles	89175	119444	122301	55436
P05	Polycarbonate shingles	67644	90601	30762	0
P06	Polycarbonate shingles	38033	50997	42491	0
P07	Polycarbonate shingles	102241	136106	118257	0
P08	Polycarbonate shingles	67186	89888	92127	0
P09	Polycarbonate shingles	70824	94886	97156	0
P10	Synthetic rubber	70512	94468	96728	73677
P11	Asphalt polymer	103501	144597	148624	154360
S01	Granite tiles	53144	65331	15404	0
S02	Granite tiles	51792	69388	12214	0
S03	Granite tiles	52061	58487	29247	0
S04	Granite tiles	51637	65597	17171	0
S05	Slate tiles	162928	218300	223523	202646
S06	Gravel	90647	121420	124329	129559
S07	Gravel	88273	118273	121123	126215
W01	Wood shingles	110704	148314	151494	151594

Supporting information 1.3 Spectral library

The spectral library of rooftop materials in the urban area (Zambrano-Prado et al., 2017) can be acquired free online at https://ddd.uab.cat/record/196065

Appendix 2. Supporting information for chapter 5

Assessment of the food-water-energy nexus suitability of rooftops. A methodological remote sensing approach in an urban Mediterranean area

Supporting information 2.1. Criteria to integrate FWE systems for commercial and non-profit purpose

Phase 1: Study area characterization

The characterization of the study area is based on the following criteria:

a) Urban features. It is important to know the urban context, such as urban form, population density, use and typology of building.

b) Climatic conditions. Resource potential is crucial to determine the feasibility for integrating FWE systems. Sunlight amount is necessary for growing food and determine suitable crops, directly affecting crop yields. Solar radiation reached by plants directly impacts the photosynthetically active radiation (PAR), which describes the generally accepted light wavelengths between 400 and 700 nm useful for photosynthesis. The relationship between solar radiation (normally measured in global horizontal radiation, in W/m^2h) and PAR (measured with the Photosynthetic Photon Flux Density, in $\mu mol/m^2s$) cannot be determined accurately unless values for each individual wavelength are known (Langhans & Tibbitts, 1997) Here, an approximation conversion value is calculated using global broad bandwidth and PAR measurements taken during the 2019-2021 period in the Barcelona area in order to give a more precise on-field data. The resulting average conversion factor from recorded daily solar radiation to PAR values used in this study was 2.21 ± 0.01 (CI 95%) to integrate average annual atmosphere conditions that influence this factor. This factor is in line with the 2.29 and 2.12 theoretically reached in daylight and blue-sky conditions respectively (Thimijan & Heins, 1983), which is normally referred in literature. This ables to calculate the cumulative measurement of total daily photons reached by plants in MJ/m^2d (known as day light integral, DLI, normally expressed in $\mu mol/m^2s$) in order to explain the ideal light requirements that saturate the leaf net photosynthetic rate to maximize plant growth (Kozai et al., 2015).

Rainfall over the year plays a key role in determining whether RWHS can compete with other water supply systems, as a general rule, rainfall should be over 50 mm/month for at least half a year or 300 mm/year (FAO, 2014; Worm & van Hattum, 2006).

2.2.2 Phase 2: Urban and architectural requirements

To identify suitable roofs, this phase considers criteria at urban and architectural scales.

a) Urban. Planning and building laws and codes must be considered to ensure that the integration of FWE systems meet legal requirements.

Cities are composed of diverse building types and a variety of uses, such as educational, housing, health, public services, commercial and industrial. Building use is important criterion that can define the purpose of the FWE systems. For example, educational buildings can integrate these systems for educational and self-sufficient purposes (Nadal et al., 2019), commercial and industrial buildings for commercial purposes (Nadal et al., 2017; Sanyé-mengual et al., 2015; Sanyé-Mengual, Martinez-Blanco, et al., 2016) . Building uses are usually defined in urban planning and local ordinances.

b) Architectural. The characterization of buildings roofs (area, slope, material, radiation and sunlight access) is needed to identify feasibility areas.

Roof area. A minimum roof area of 500 m^2 is needed for integrating UA for commercial purposes (Nadal et al., 2017). A minimum roof area of 13 m2 can satisfy the vegetal demand for one person using soil less agriculture systems (Boneta et al., 2019) this was considered for non-profit purpose.

Taking into account the energy consumption and the yearly operation and maintenance cost, photovoltaics (PV) suitability requires at least a minimum roof area of 100 m2 for commercial use and 24 m2 for residential use (Spertino, Di Leo, & Cocina, 2013). The established areas can be geographically sensitive due to major consumption typical at latitudes with less sunlight hours.

Roof slope. For integrate UA systems, slope of roofs must be flat ≤ 10% (Nadal et al., 2017). For rainwater harvesting systems (RWHSs) and PV systems, roof slope was not considering, assuming that PV panels are adjustable.

Solar radiation. Energy systems require solar radiation higher than 13 to 14 MJ/m2 per day (Nadal et al., 2017). The amount of radiation is essential for growing food, in this work was established three levels of day light requirements for crops. Daily light requirements (measured with DLI) vary depending on the crop and its photoperiod, which range between 6 to 35 mol/m2d. Current methodologies to identify potential urban agriculture areas normally define a target DLI value between 20 – 25 mol/m2d, originally expressed in MJ/day (Benis et al., 2017a; Nadal et al., 2017; Sanyé-mengual et al., 2015). Other literature refers to the minimum average solar radiation of 8.5 MJ/m^2d defined for Mediterranean crops as reported by Nisen et al. (1998). These DLI targets usually satisfy light requirements for multiple selected crops or single species like tomato plants, which is a reference crop for agriculture studies. However, these are high compared to the optimal DLI requirements for other valuable crops as microgreens (see Table 1), underestimating the urban potential area that could grow low and medium-DLI crop types. Here, three groups of crops are classified according to their optimal daylight needs (i.e., maximum yields), even lower light levels will linearly decrease yields (Kozai et al., 2015) within acceptable crop yields and environmental performance (Rufí-Salís et al., 2020) Grouped DLI requirements are expressed in mol/m2 and in MJ/m^2 daily and annually in order to facilitate comprehension and applicability of this workflow (see light conversion factor section). Hence, the approach here is to adapt the crop species to the available urban solar radiation, since adapting the light requirements with additional LED lightning would lead into an excess of energy needs with high environmental costs (Benis et al., 2017a).

Roof material. Roof materials are essential data to integrate these systems, if a roof does not have the necessary load-bearing capacity to support the weight of the system, it will not be possible to install a system on it. A minimum load-bearing capacity 200 kg/m2 is required (Nadal et al., 2017). In the case of RWH, the quality and quantity of rainwater harvested from roofs are significantly affected by roofing materials (Farreny et al. 2011).

Phase 3: Self-sufficiency indicators. Production of FWE systems must be calculated to obtain the production and the self-sufficiency potential. To do this, the following three steps are required:

a) Resource production. Potential production is used as indicator to assess the FWE systems integration and to estimate the degree of self-sufficiency. Suitable crops must be identified based on household typical food diet, for this reason, suitable crops can be geographically sensitive. Irrigation water requirements of crops data are needed. Water demand, depend on the type of crops and growing methods an systems, if this information is not available for the selected crop in and the geographic region of the study area, data of evapotranspiration (ETo, mm) is required to calculate (Khangaonkar & Mehaute, 1991). The following considerations should be taken to quantify resource production:

Food. To quantify crop yield values, growing method (RTGs or open-air) and growing system (soil less or soil-based) must be considered.

Water. Average rainfall data and runoff coefficient (RC) is required to estimate the potential rainwater harvesting on roofs. RC varies according to roof material from 0.9 to 0.6 (Farreny et al., 2013).

Energy (PV). The technology for PV for example the most commonly in the market.

c) Self-sufficiency. For this phase, two criteria are necessary: potential production and household consumption. The potential food for self-sufficiency is calculated by dividing the potential production (food, water, energy) by the average consumption of the food (kg·person·year), water (lts·person·year) and energy (kWh·person·year) in the study area, resulting in the total number of people whose demand is satisfied.

Supporting information 2.2. Average yield values of tomatoes and lettuce

Growing method	Growing System	Crop type	Crop yield (kg/m^2)	growing season	Reference
RTGs	soil-less	Tomatoe	15.3	Spring-summer	Sanjuan-Delmás et al. (2018)
Open-air	soil-less	Tomatoe	5.8	Spring-summer	Boneta et al. (2019)
RTGs	soil-less	Lettuce	8.36	Spring and autum	Rufí-Salís et al. (2020)
Open-air	soil-less	Lettuce	3.85*	Anually	Boneta et al. (2019)

*Lettuce crop yield value in open air considers a policultive of vegetables production. Production in RTGs considers passive heating.

Supporting information 2.3. Water requirement for tomatoes and lettuce irrigation

Growing method	Growing System	Crop type	growing season	Water use (L/kg)	Reference
RTGs	soil-less	Tomatoe	Spring-summer	66	Rufí-Salís et al. (2020)
Open-air	soil-less	Tomatoe	Spring-summer	130.5	Boneta et al. (2019)
RTGs	soil-less	Lettuce	Summer and autumn	77.6	Rufí-Salís et al. (2020)
Open-air	soil-less	Lettuce	Spring-summer	130.5	Boneta et al. (2019)

Supporting information 2.4. Light conversion factor

Light conversion factor has been studied with on-field measurements in the Urban Agriculture facilities in the Institute of Science and Technology (ICTA-UAB) in the compounds of Universitat Autònoma de Barcelona in the city of Cerdanyola del Vallès, in the Barcelona region. The weather station in this facility is equipped with a global solar radiation (Hukseflux LP02, second class pyranometer) and a PAR Quantum sensor (SKP215 with a ±5% accuracy, typically <±3%) which measures incident quanta between 400 and 700 nm. A CR3000 datalogger from Campbell Scientific measures data every 5sec, recording the averages at hourly intervals during the 2019 to 2021 period.

In order to study the Day Light Integral of crops, the sum of all incident radiation of both sensors has been summed per day and then divided in order to calculate the conversion factor from global radiation (W/m^2) to PAR (PPFD, in µmol/m2s). The obtained values in a box plot are presented in detail in Figure A1. Note that significant differences exist between year quarters, being the second and third quarter greater than the first and fourth. However, as the assessment here is annual based, a unique average value of 2.21 ± 0.01 (CI 95%) for all year has been used.

Grouped DLI requirements are expressed in mol/m^2 and in MJ/m^2 daily and annually in order to facilitate comprehension and applicability of this workflow to other solar measurement sites. It is important to note that vegetative crops do not require significant lower DLI during the early stage of the plants development, while fruiting crops like tomatoes require significant lower levels (from 2 to 13-20 mol/m^2d) during the vegetative growth stage compared to the fruiting phase up to 40 mol/m^2d (Schwarz et al., 2014). Therefore, when calculating the annual light needs for tomato plants in the high DLI group, an average value between 20 and 25 mol/m^2d is assumed (i.e., considering that the vegetative phase lasts the same period as the fruiting phase (Philips Lighting Horticulture, unpublished work).

The growing period has been considered according to the average months in the Mediterranean area, excluding the coldest months (December and January) (FAO, 2013).

Similarly, one short tomato crop lasting 6 months has been also considered according to common practices in the Mediterranean climate while an extended tomato crop of 8 months has been considered for rooftop greenhouse farming. Finally, an average solar transmissivity radiation of 70% has been considered, even this could vary according to roof slope and orientation (Castilla, 2005).

Table 3. Crop classification according to DLI requirements.

Day light requirements (DLI target)		MJ/m²·year OA / RTG	Crop specie	Optimal DLI (mol/m²·day)	Reference
Low	> 6 mol/m² > 2.7 MJ/m²	> 800* > 1400*	Microgreens	6–12	Kozai et al. (2015) Verlinden (2020)
			Small vegetative crops, green shoots	< 12	Kozai et al. (2015)
Medium	> 12 mol/m² > 5.4 MJ/m²	> 1650* > 2800*	Lettuce	12–17	Albright et al. (2000)
			Leafy crops	12–17	Albright et al. (2000)
			Vegetable seedlings	13	Fan et al. (2013)
			Strawberries	13	Kozai et al. (2015)
			Young / low-wire tomato (e.g. cherry)	13–17.3	Ingestad et al. (1994)
High	> 22 mol/m² >10 MJ/m²	> 2000** > 3800***	High-wire tomato	Avg 22–26 Up to 30–35	Spaargaren (2001)
			High-wire tomato	Avg 22–29 Up to 30–40	Schwarz et al. (2014)

* Considering 10 and 12 months of crop season for OA and RTG farming, respectively.
** Considering 6 months of crop season equivalent to one short tomato crop.
*** Considering 8 months of crop season equivalent to one extended tomato crop.

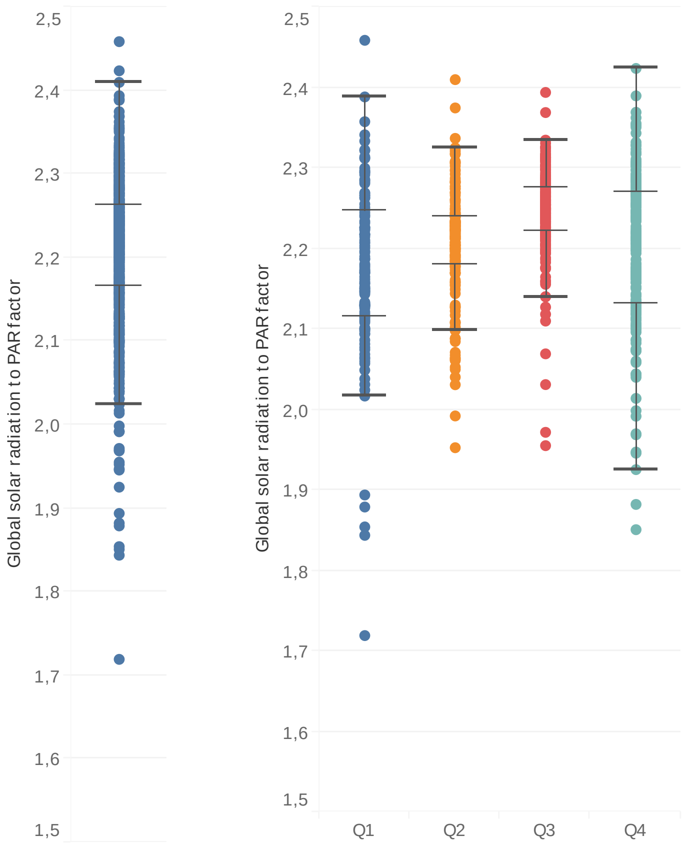

Figure 1. Annual and quarter conversion factor values.

Supporting information 2.5. Downscaled analysis water self-sufficiency irrigation

The Figures 2 and 3 show the water self-sufficiency per system and crop per month. For tomato cultivation in greenhouses, self-sufficiency ranges from 28% to 48%; tomato in an outdoor system from 34% to 75%; lettuce in greenhouses from 44% to 100% and lettuce in the open air from 51% to 100%.

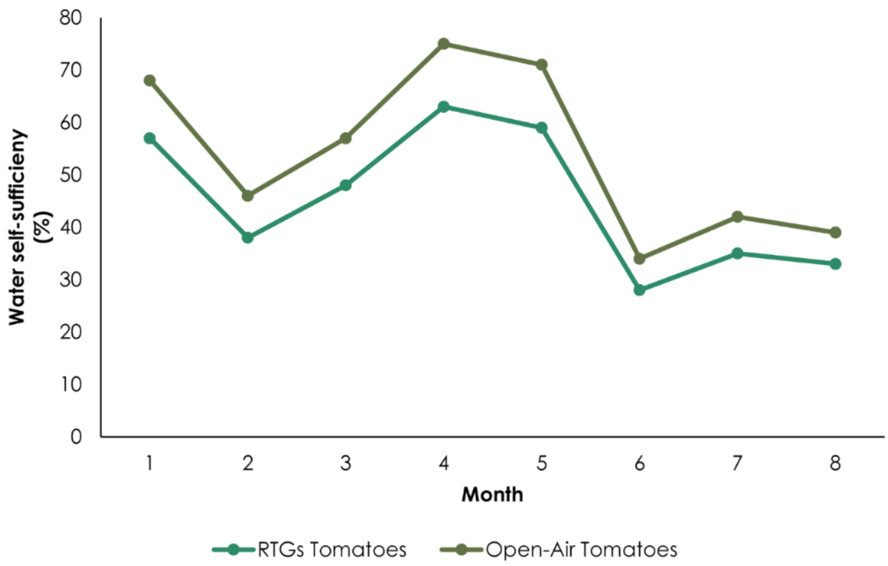

Figure 2. Water self-sufficiency irrigation for tomatoes crop per month.

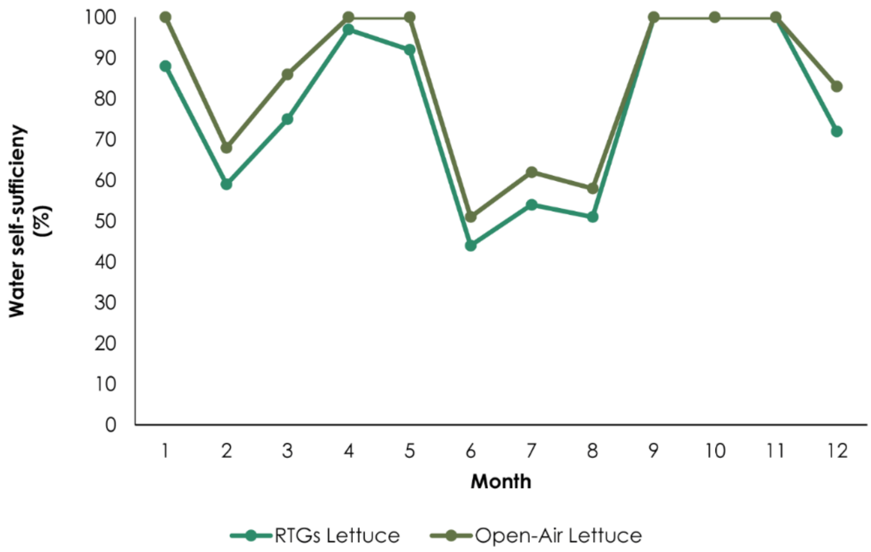

Figure 3. Water self-sufficiency irrigation for lettuce crop per month.

A smaller-scale analysis contributes to a better understanding of water tank sizing and its relation to weight (aspects not included in this work). Other studies carried out at a smaller scale (building and neighborhood) found for the city of Callafel (Catalonia, Spain) tank sizes of 4 m^3 for roof area less than 200 m^2 could only meet 20% and 57 m^3 water tank could supply from 76 % to 99% according to roof area from 201 to 1000 m^2 for toilet flushing and laundry (Petit-Boix et al., 2018); in Barcelona city a 7 m^3 cistern size could supply water demands (Toboso-Chavero et al., 2018). It is necessary to evaluate water tank size at the building level on a case-by-case basis or as a whole for those with the same typologies.

Supporting information 2.6. Population density of each municipality and the self-sufficiency potential

Table 4 shows a comparison between the highest and lowest density municipalities in the study area and the differences in self-sufficiency by system. The greatest difference is in the food (total tomato production) and water, exceeded by up to 65 and 13 times, respectively, by the municipality with the lowest density. In addition to population density, other factors can affect the potential, the urban form, the building typology, and its characteristics (mentioned above), the number of inhabitants per house, and the consumption differences.

Table 4. Population density and self-sufficiency by system

Municipality	Population density (inhabitants/km2)	Self-Sufficiency (number of times)			
		Food Tomato	Food Lettuce	Water	Solar Energy
Badia del Vallès	14,426.88	9.7	1.0	2.0	0.9
Cerdanyola del Vallès	1,889.39	74	7.4	15.5	6.5

For self-sufficiency analysis the potential area of the total study area is considered.

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Appendix 3. Supporting information for chapter 6

Potential key factors, policies, and barriers for rooftop agriculture in EU cities: Barcelona, Berlin, Bologna and Paris

Supporting information 3.1. Description of survey sections

(1) Survey description and context. The first section set the context and described the Fertilecity II project with a brief description of the previous workshop and survey objectives.

(2) Stakeholder information. The second part of the survey consisted of six questions. This section aimed to identify both the sector (e.g., architecture office, start-up, research center, public administration, landscape office) and the stakeholder city (Barcelona, Berlin, Bologna, or Paris) where the stakeholders developed their work regarding RUA. The participants' email addresses, name of institution and description, and position in the institutions were removed from the analysis. Sensitive data, such as name, gender, and phone number, were not required.

(3) Key factors for integrating RUA. This section aimed at identifying the relevance of twelve key factors for implementing RUA and included the following subjects: environmental, social, technological, educational, and economic.

(4) Context factors that hinder or promote RUA. Section four of the survey focused on evaluating the perceived effect on RUA diffusion of thirteen context factors.

(5) Public policies to promote RUA. This section aimed to identify the perceived effect on the RUA diffusion of eleven policies.

(6) Barriers to integrating RUA. This section focused on identifying the frequency of the presence of the barriers to integrating RUA. In total, 24 barriers were evaluated. The barriers were divided into five topics: architectural, urban, technical, economic, and social.

Supporting information 3.2. Complete international experience workshop results

Berlin. It is highlighted that UA is not a recent development and that urban gardens are regulated by the government. In the planning of the territory, UA has been recognized as beneficial for the city in terms of its social and biodiversity factors. In the conceptualization of green space, urban gardens are included in the zoning for land use. Another aspect to highlight is that the public sector provides tools to citizens and practitioners of UA. The guide "There is something growing on the roof" (2015) represents an especially interesting tool because it allows to clear concerns in the recipient and constitutes a good resource to encourage UA practice; it is also a sign of the city's commitment to RUA practices. Some barriers, such as lack of a specific legal framework, health risks perceived by consumers, high-cost infrastructure, and the lack of economic benefits limit RUA integration.

Bologna. The implementation of RUA is presented using simple technologies and with social and educational purposes; however, there are legal gaps and a lack of a specific legal framework for RUA. There are incentives and legislation for the implementation of green roofs, for example, the Stability law (2016), although not for agricultural production. There are no policies or regulations, especially for addressing RUA. Some policies can interact with the RUA, such as The Milan Urban Food Policy Pact (2015), an international agreement that was signed by 211 cities from around the world. During the workshop, the rooftop community garden (2010) in the Emilia-Romagna Region supported by the Bologna City Council was introduced to promote intercultural dialog and social cohesion between the inhabitants of social housing. According to an expert from Italy, "among the policies that could affect RUA, the following are considered: legal instruments (laws and ordinances), economic tools (taxes, incentives, and subsidies), educational tools, urban planning instruments (viability of buildings)".

Paris. The Paris Climate Action Plan is committed to a new urban model. One of their objectives is greening the city; 100 hectares of green roofs and walls must be installed, one-third of which will be devoted to urban agriculture by 2020. In this sense, Paris is a pioneer in the integration of RUA through the Parisculteurs program. From the modification of the Paris Local Urban Plan (LUP) for integrating RUA in the city and the call for Parisculteurs, three objectives must be achieved: to improve the state of knowledge on regulations and technical constraints, to link landowners with project holders, and to promote urban agriculture knowledge and debates among stakeholders and the public. In the first call for RUA initiatives in 2016, the city of Paris supported 33 projects that involved 550,000 $m^{2,}$ most of which have educational purposes and integrate greenhouses and hydroponic growing systems. The city of Paris financed the work necessary to operate the sites, and revenue was generated to cover the costs. In the future, profitability will be taken into account. Regarding technical regulations, two guides have been created: a regulation that concerns health problems and administrative processes and standards related to building accessibility. The possibility of selling food produced on rooftops could be allowed if the standards are followed. Architectural legal barriers concerning historical buildings have also been presented. Another limitation is that planting a large surface may not be as quick or economical for the city of Paris.

In Barcelona, some programs have been implemented to support urban gardens. Existing legislation focuses on the promotion of green roofs (not for food production), and the guide Living Roofs, and Green Roofs was developed in 2015 to support green roofs and activities in roof areas. According to the Technical Director of the Municipal Institute of Urban Landscape from the Barcelona City Council, programs for promoting green roofs have been unsuccessful; for this reason, subsidies have been implemented. There are two main barriers to integrating RUA:

• Legal. The urban metropolitan plan does not contemplate the use of agricultural land in Barcelona.

• Social. Most of the building residents perceive green roofs as a problem, especially regarding maintenance issues.

The Technical Director of the Municipal Institute of Urban Landscape indicated some proposals to promote RUA:

• Consider UA on the roof as thermal insulation.

• Grant competitions. Consolidate the annual green roof contest, where projects can integrate urban agriculture.

• City council building and urban ordinance. The city council analyzes changes in buildings and urban codes to promote RUA. A proposal could be made to permit the use of roofs for green cover, energy generation, water catchments, and agriculture.

According to the Environmental Technician from the Barcelona City Council, there is currently legislation for the development of municipal social gardens at the ground level. However, restrictions on commercializing the products of municipal social gardens are an economic barrier. There are also problems regarding food distribution, for example, food that is produced in Barcelona but consumed in Almería. He also indicates that technology in food production undermines the social dimension of urban agriculture.

In the opinion of the Director of the green roof projects office, the main barriers to integrating RUA are as follows:

• Urban planning. Land-use restrictions on agriculture in the city and the lack of legislation that permits building licenses for this type of infrastructure.

• Social. Building owners or communities of neighbors, in some cases, communities of neighbors refusing to build a green roof.

• Economic. Interested investors may lose interest if they are not able to commercialize the product.

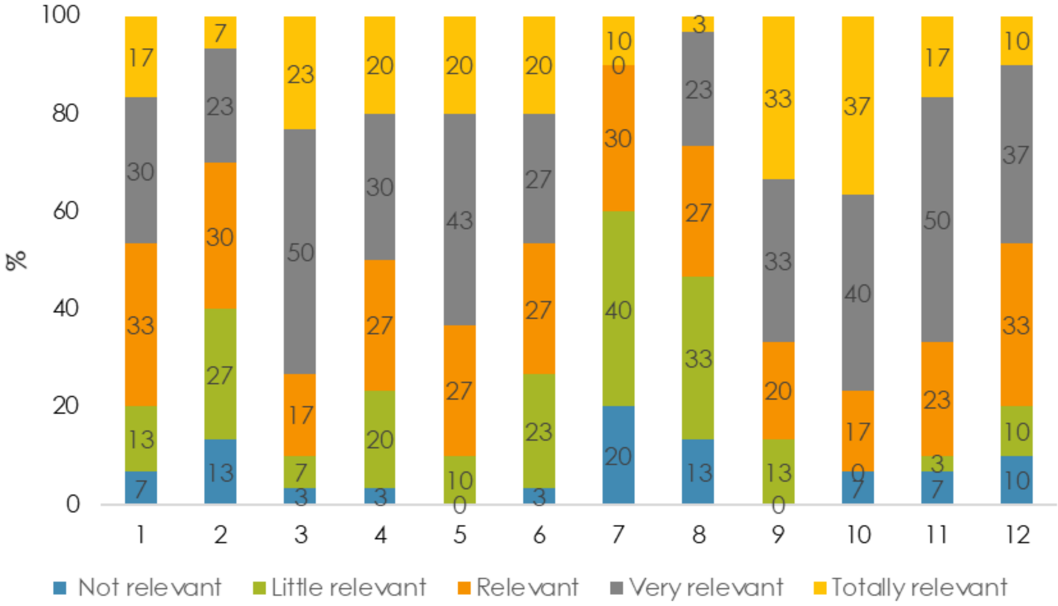
Table 5. Brief description of the existent policies and guides introduced in the workshop for supporting UA in Berlin, Italy, Paris, and Barcelona.

City/ Country	Policy	Guide	Name	Description
Berlin	●		Biodiversity strategy Berlin	The main objective is to preserve biological, the strategic goals address four subject areas, species and habitats, genetic diversity, urban diversity, and society.
	●		The Berlin Energy and Climate Protection Programme 2030 (BEK 2030)	Aim to reduce the general energy demand within the city. There will also be a shift in the transport sector, towards a city where public transport and cycling are more attractive in order to encourage people to leave their cars at home. Greening within the city will be extended, including roofs and facades and fostered in order to make the city more resilient to rising temperatures.
		●	There´s is something growing on the roof (2015)	The guide about rooftop greenhouses discusses projects experiences from pilot projects as well as offers expert advices from urban agriculture stakeholders
	●		Land use planning	Allotment gardens or urban agriculture are integrated in Berlin land use planning.
Italy	●		Milan Urban Food Policy Pact (2015)	The first international protocol that calls for cities to develop sustainable food systems that grant healthy and accessible food to all, protect biodiversity and reduce food waste.
Bologna			*Support to create rooftop community garden (2010)	The Emilia-Romagna Region and Bologna City council promoted the creation of the first rooftop community garden on the social housing buildings of Via Gandusio.
Paris	●		Paris climate action plan	With over 500 measures in several topics (building, transportation, energy, food, waste, lifestyle, mobilization, finance), Paris Climate Action Plan is a concrete implementation of the commitments of France and lead Paris to carbon neutrality.

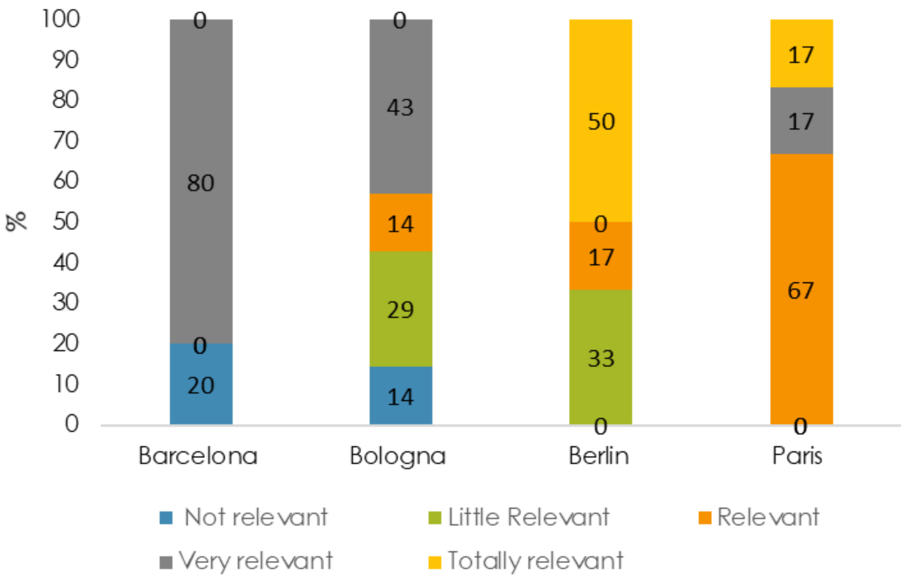
		*Les Parisculteurs	The main objectives of this programme are to improve the state of knowledge on regulations and technical constraints, to link landowners with project holders, and to promote urban agriculture knowledge and debates amongst stakeholders and public.
	●	Mon projet d'agriculture urbaine en Île-de-France Guide pratique des démarches réglementaires (2016)	The guide explains the administrative and technical rules that apply to an agricultural production project in urban areas
	●	Living Roofs and Green Roofs (2015)	The guide promotes and the uses of roof spaces and explain the social benefits as well as offered technical information.
	●	Urban gardens	This programme is aimed at people over 65 who are registered in the district where the garden is located. Lots are drawn to allocate plots and land is ceded for five years with an initial trial period of six months.
Barcelona	●	More Sustainable Schools	Aims to introduce sustainability in education by offering advice and resources in the centers to develop projects, urban gardens are included in this program.
	●	Pla BUITS	This program has the objective of revitalizing unused land in the city of Barcelona, through provisional public interest activities, promoted by public or private non-profit entities, favouring the involvement of civil society in the regeneration and revitalization of the urban fabric, activities include urban gardens
	●	The First Green Roof Contest (2017)	Subsides were not restricted to the integration of ornamental plants, projects could also integrate food production, rainwater harvesting, and renewable energy systems

*Programs to support UA

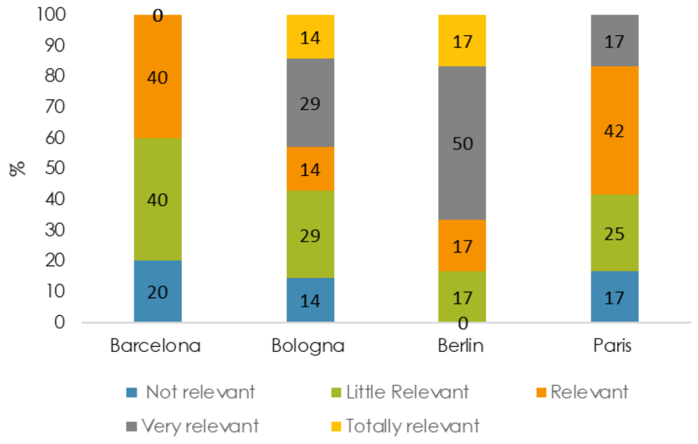
Supporting information 3.3. Perceived relevance of key factors for integrating RUA



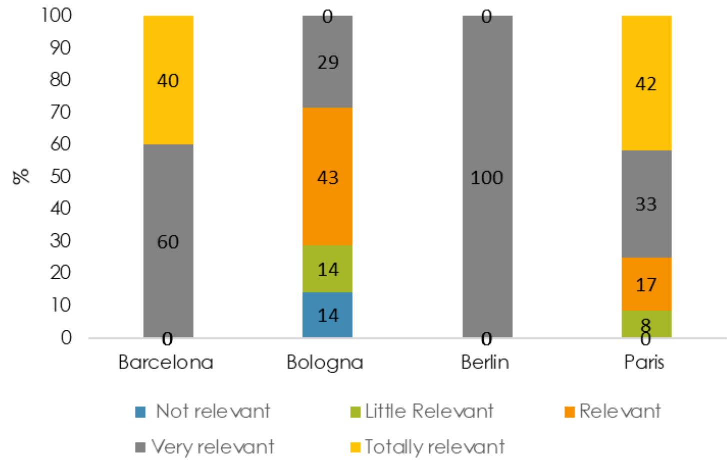
Perceived relevance of key factors in four European cities for integrating RUA. (1) Hydrologic, (2) energy, (3) environmental, (4) biodiversity, (5) vegetation, (6) food production, (7) economic, (8) waste management, (9) social, (10) educational, (11) research, and (12) technological innovation.



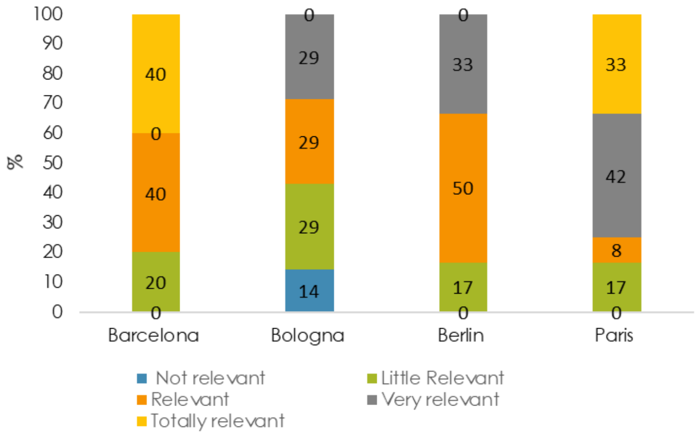
Perceived relevance of hydrologic factor in four European cities for integrating RUA.



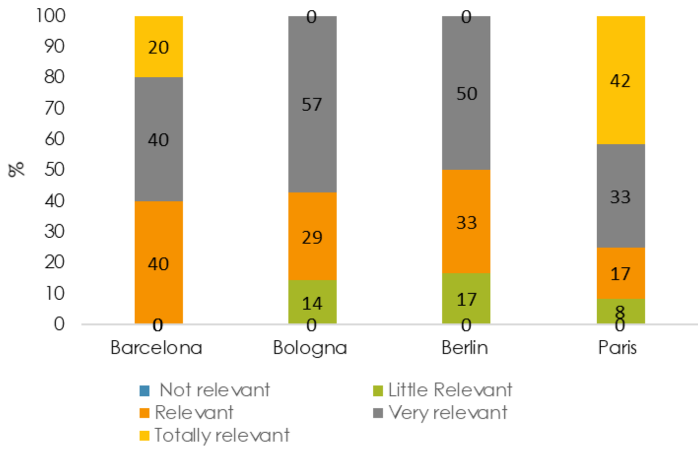
Perceived relevance of energy factor for integrating RUA.



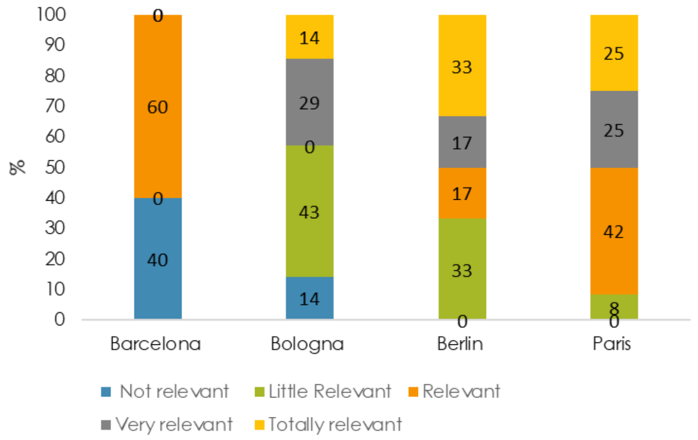
Perceived relevance of environmental factor for integrating



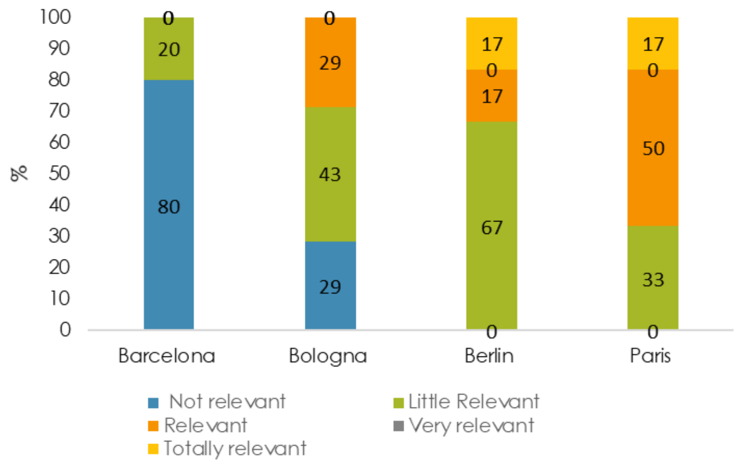
Perceived relevance of biodiversity factor for integrating RUA.



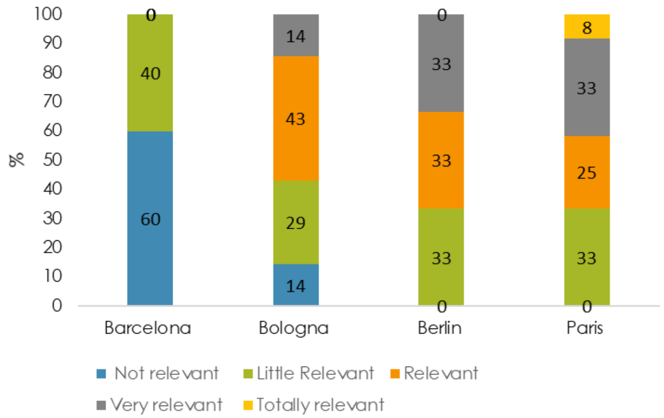
Perceived relevance of vegetation factor for integrating RUA.



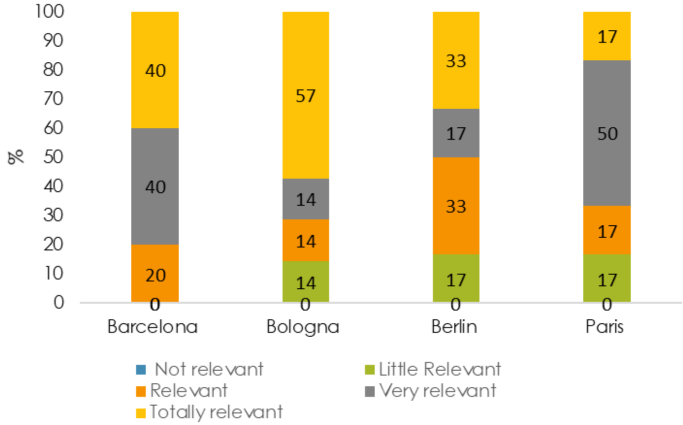
Perceived relevance of food production factor for integrating RUA.



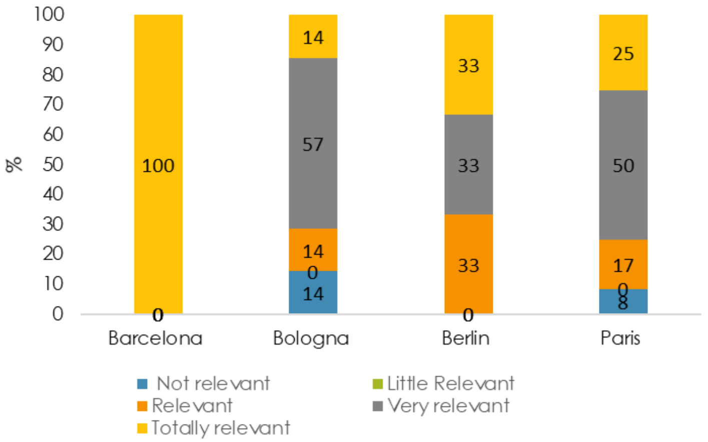
Perceived relevance of economic factor for integrating RUA.



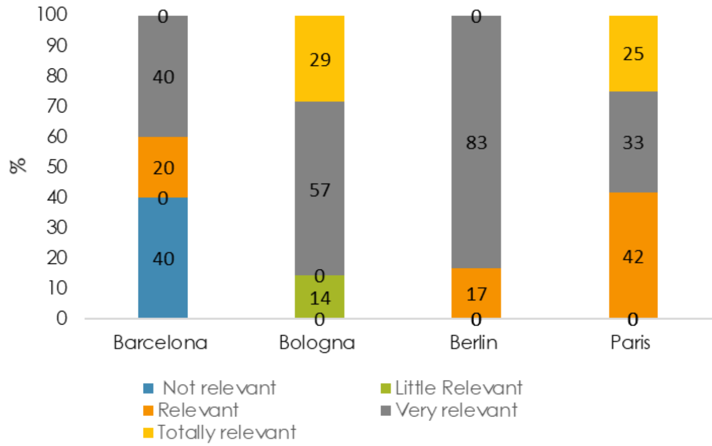
Perceived relevance of waste management factor for integrating RUA.



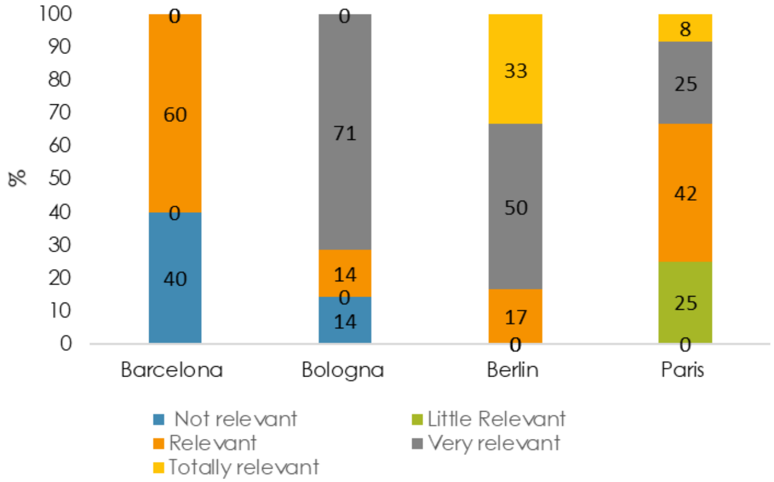
Perceived relevance of social factor for integrating RUA.



Perceived relevance of educational factor for integrating RUA.

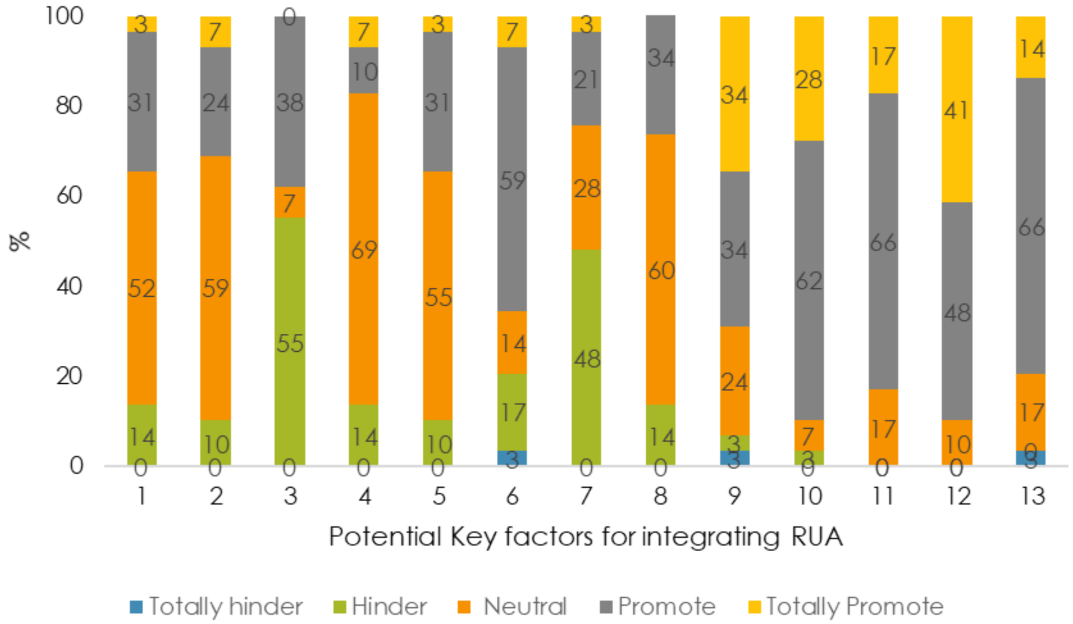


Perceived relevance of research factor for integrating RUA.

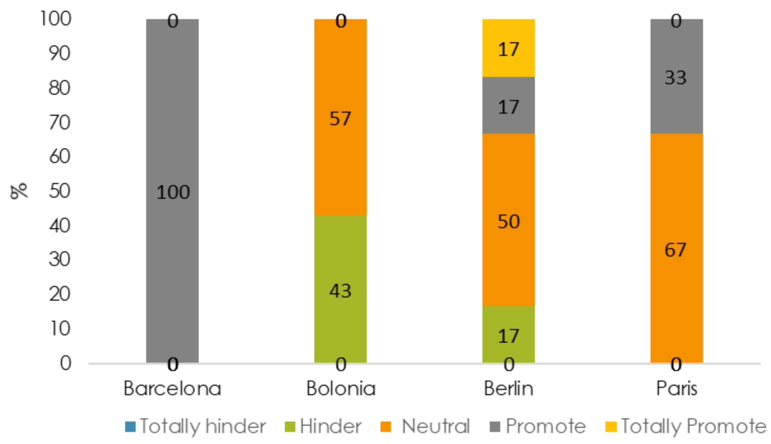


Perceived relevance of technological innovation factor for integrating RUA.

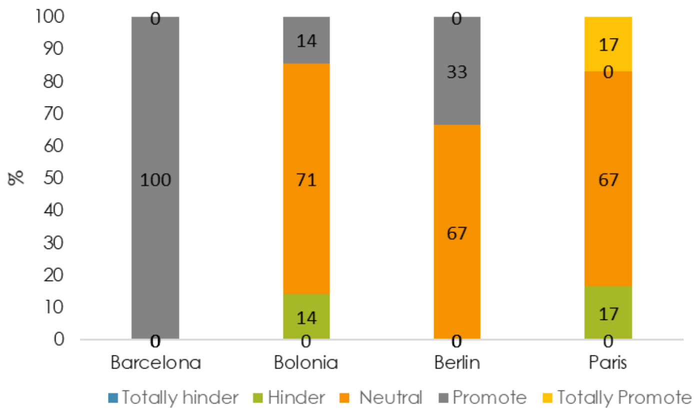
Supporting information 3.4. Context factors and perceived effect on RUA diffusion



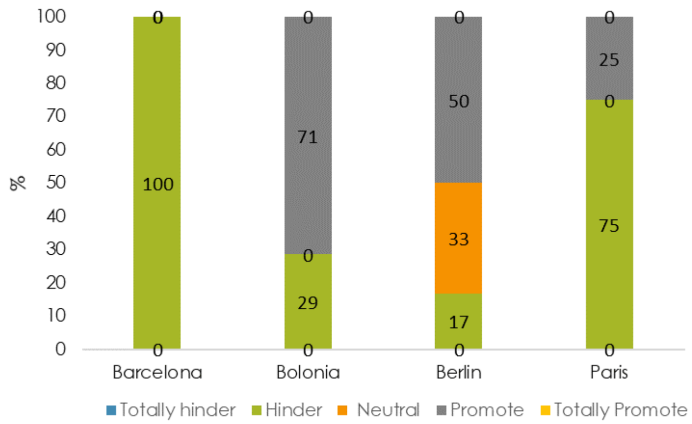
Context factors and their perceived effect on RUA diffusion. (1) Climate, (2) geography, (3) pollution, (4) economic crisis, (5) poverty/low income, (6) high cost of urban land, (7) cost of water, (8) food insecurity, (9) lack of urban cultivable soil on ground, (10) productive spaces revaluation, (11) cultural values, (12) social cohesion, and (13) social rural-urban links.



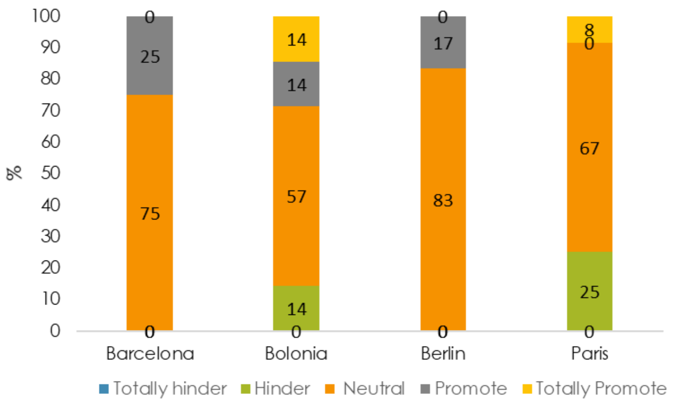
Climate context factor and their perceived effect on RUA diffusion.



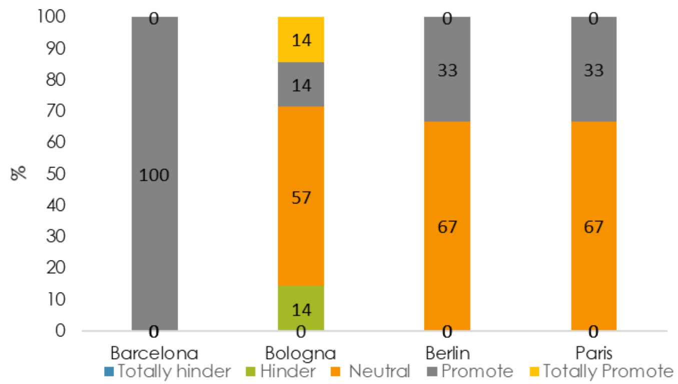
Geography context factor and their perceived effect on RUA diffusion.



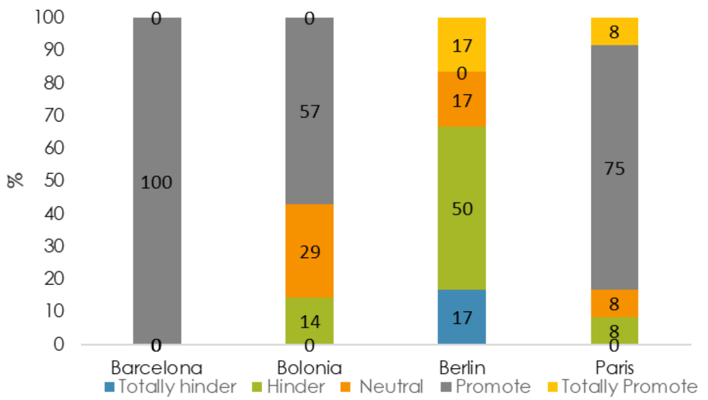
Pollution context factor and their perceived effect on RUA diffusion.



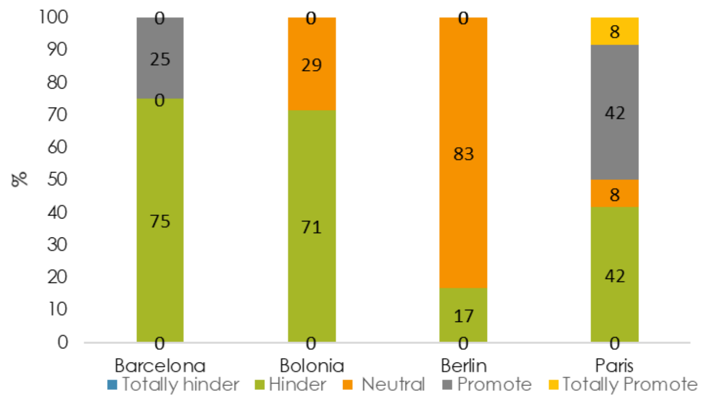
Economic context factor and their perceived effect on RUA diffusion.



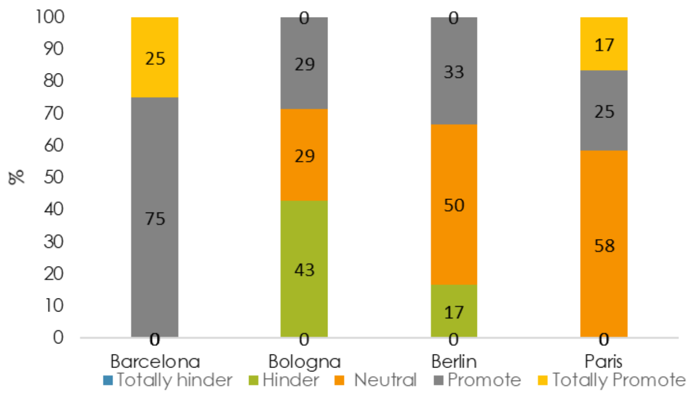
Poverty /low income and their perceived effect on RUA diffusion.



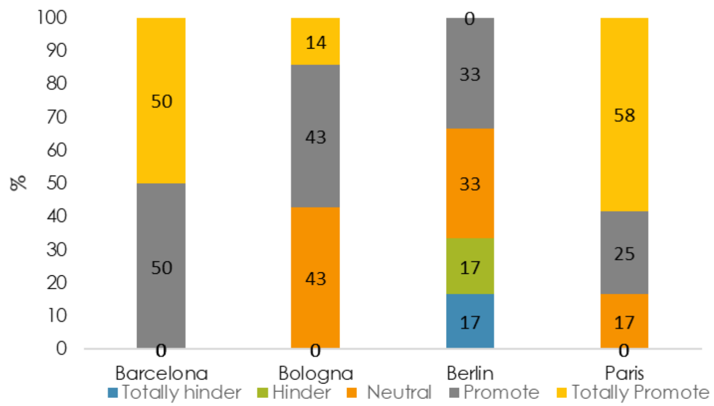
High cost of urban land and their perceived effect on RUA diffusion.



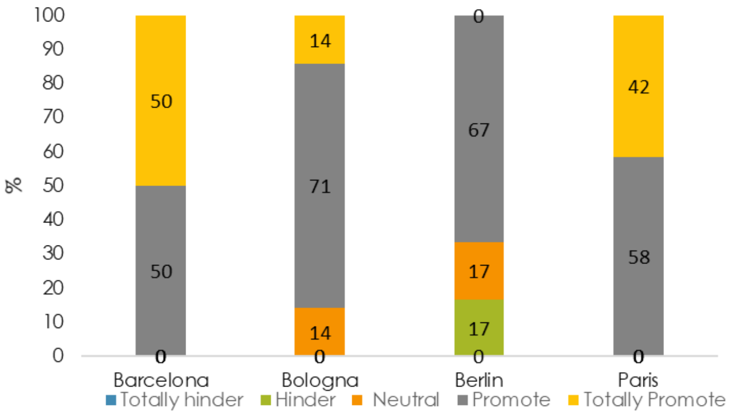
Cost of water and their perceived effect on RUA diffusion.



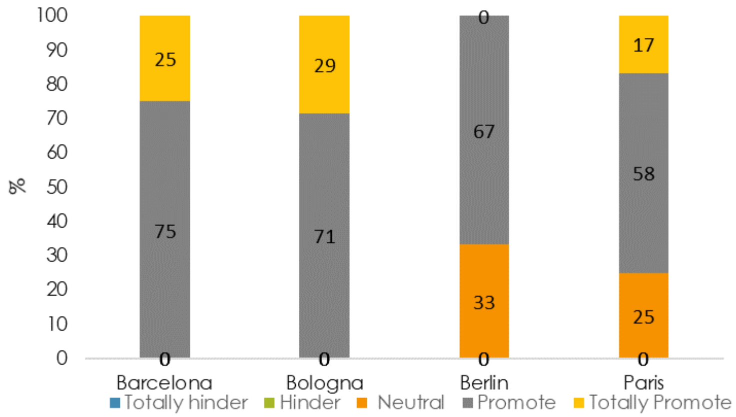
Food insecurity and their perceived effect on RUA diffusion.



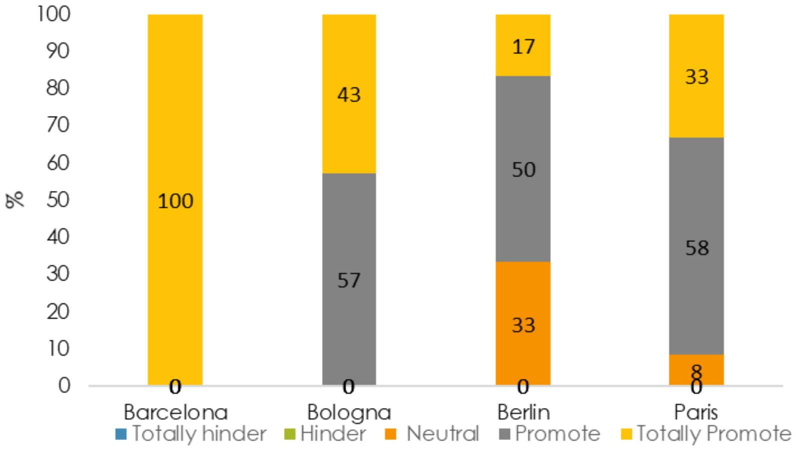
Lack of urban cultivable soil on ground and their perceived effect on RUA diffusion.



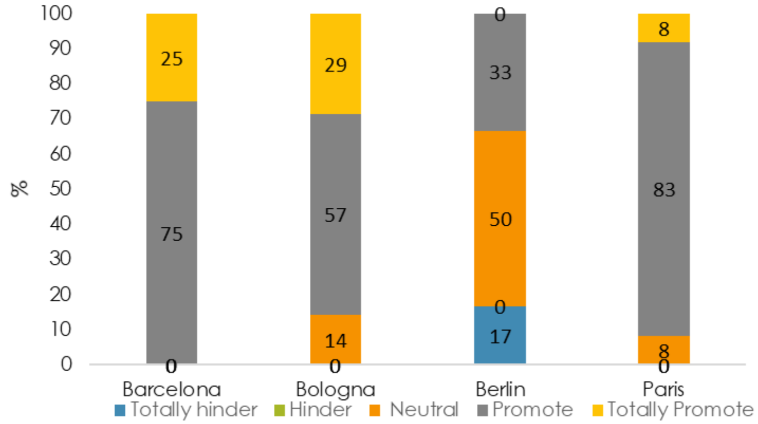
Productive spaces revaluation and their perceived effect on RUA diffusion.



Cultural values and their perceived effect on RUA diffusion.

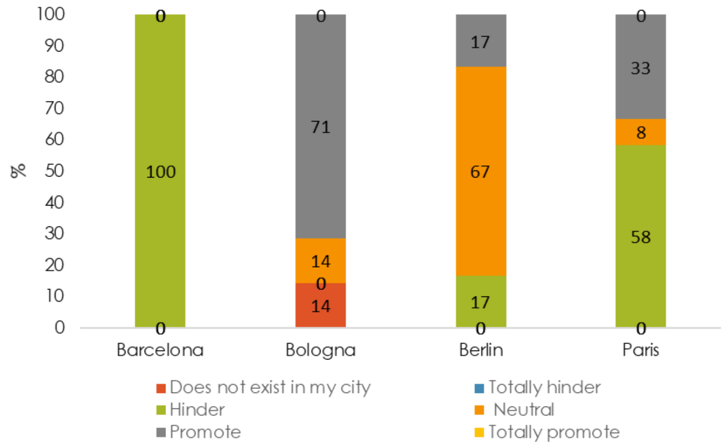


Social cohesion and their perceived effect on RUA diffusion.



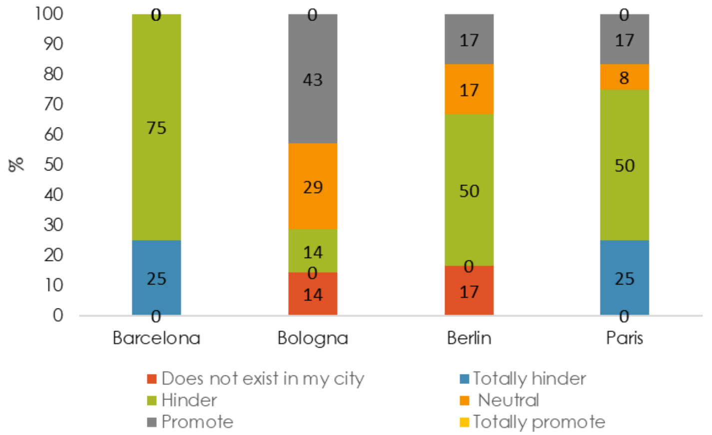
Social rural-urban links and their perceived effect on RUA diffusion.

Supporting information 3.5. Policies and their perceived effect on RUA diffusion in four European cities

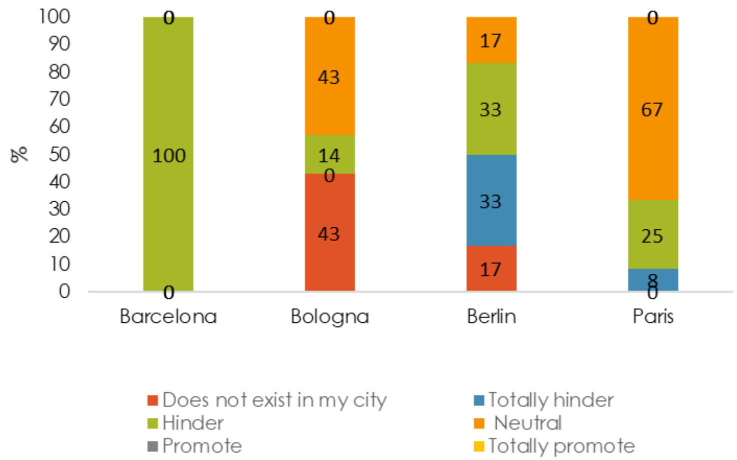


Policies that hinder or promote the integration of RUA from the stakeholder's perception from four European cities. (1) Urban planning, (2) architectural, (3) firemen, (4) food production, (5) food trade, (6) financial incentives, (7) ParisCulteurs, (8) Milan Urban Food Policy Pact, (9) educational, (10) sustainability strategy, and (11) development new technologies.

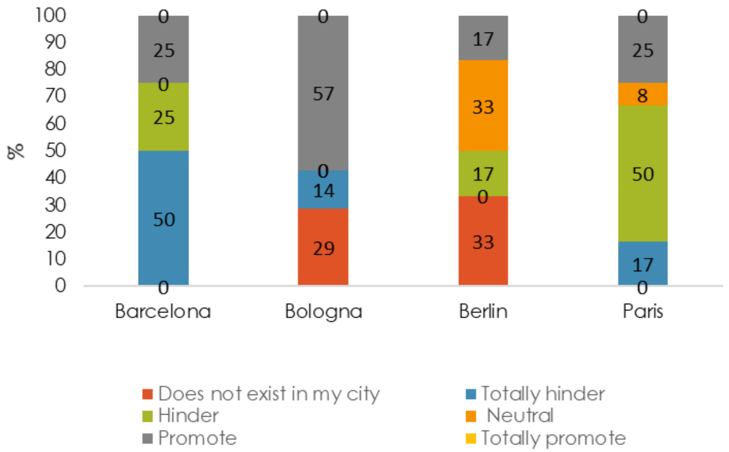
Urban planning policy and their perceived effect on RUA diffusion.



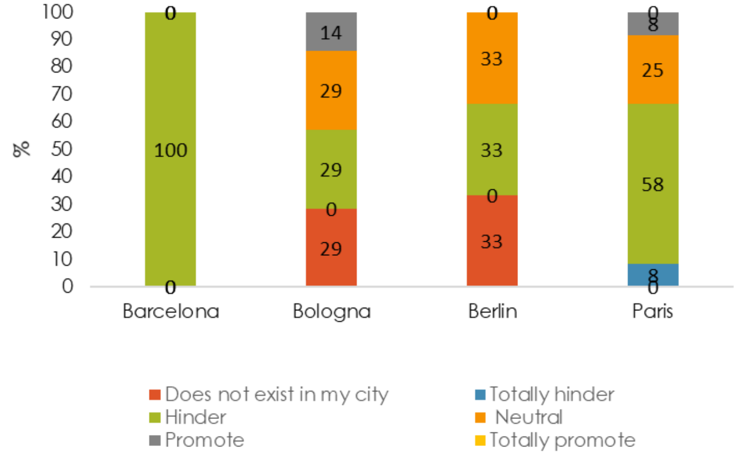
Architectural policy and their perceived effect on RUA diffusion.



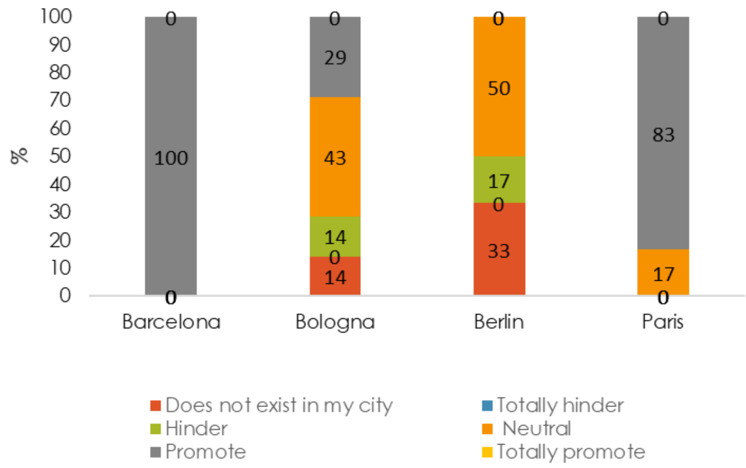
Firemen policy and their perceived effect on RUA diffusion.



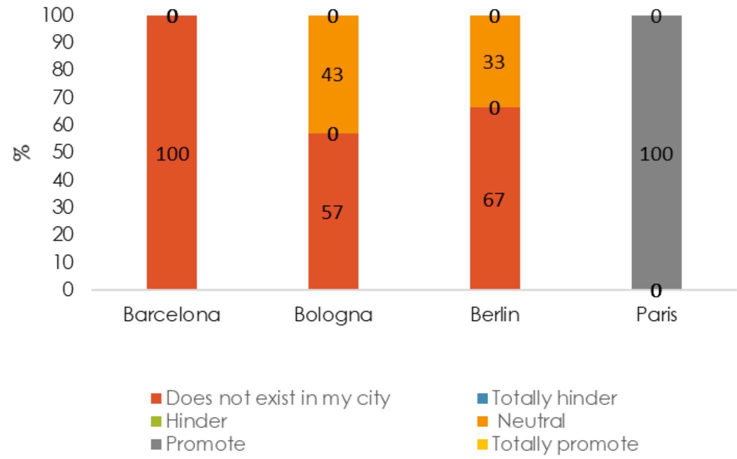
Food production policy and their perceived effect on RUA diffusion.



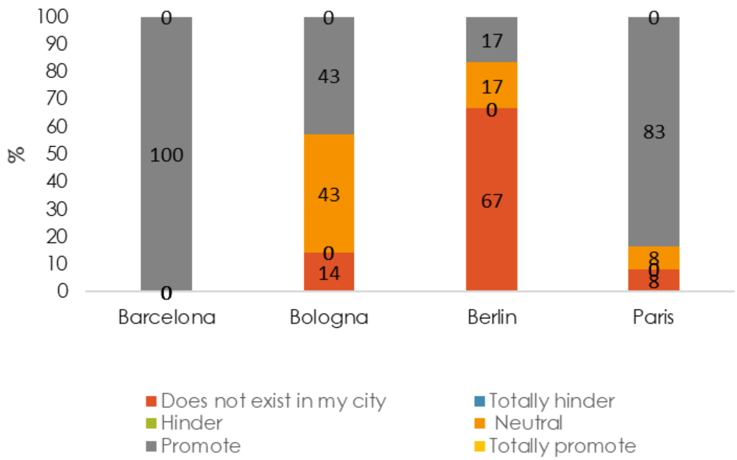
Food trade policy and their perceived effect on RUA diffusion.



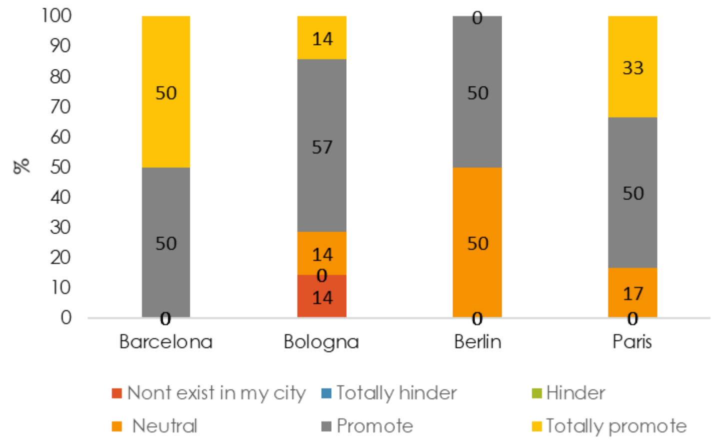
Financial incentives policy and their perceived effect on RUA diffusion.



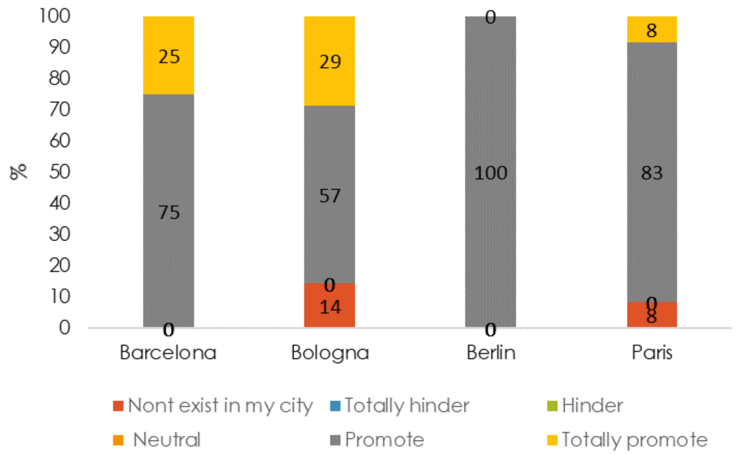
Parisculteurs policy and their perceived effect on RUA diffusion.



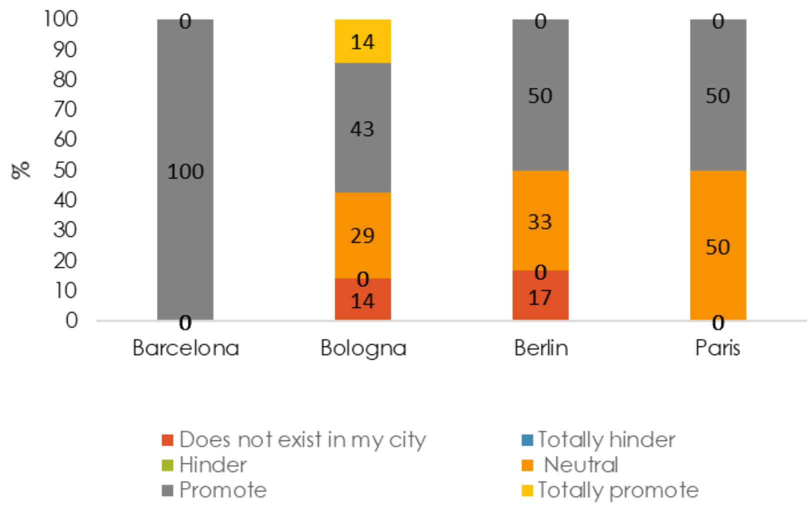
Milan Urban Food policy and their perceived effect on RUA diffusion.



Educational policy and their perceived effect on RUA diffusion.

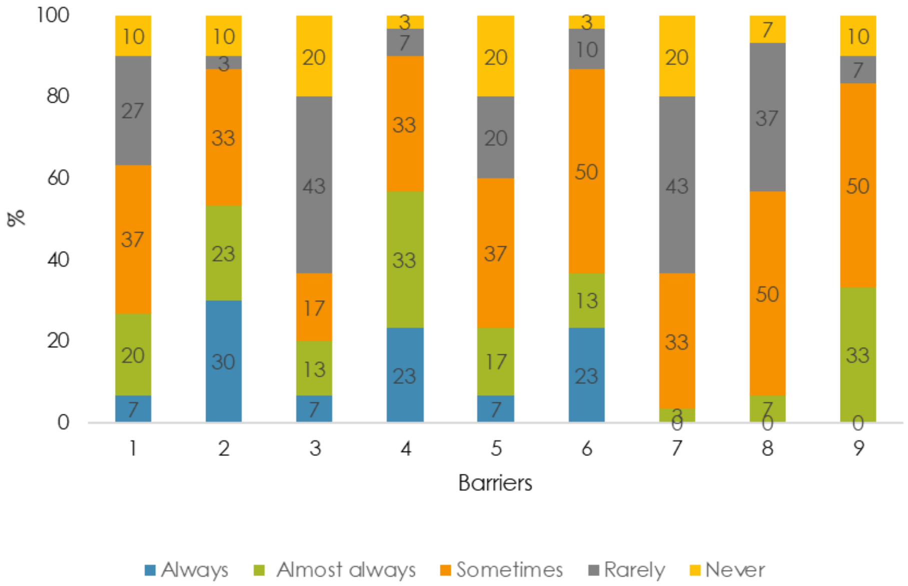


Sustainability policy and their perceived effect on RUA diffusion.

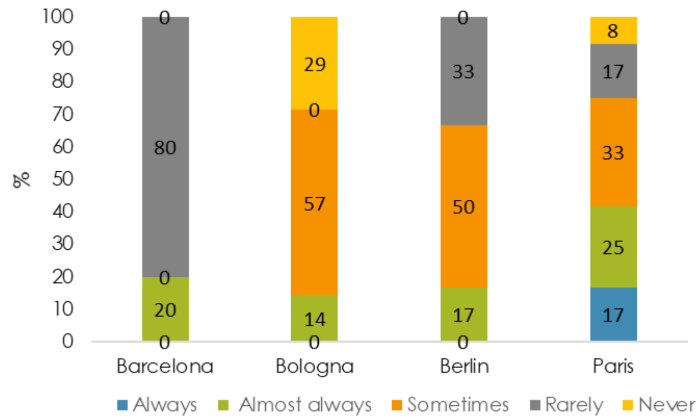


Development of new technologies policy and their perceived effect on RUA diffusion.

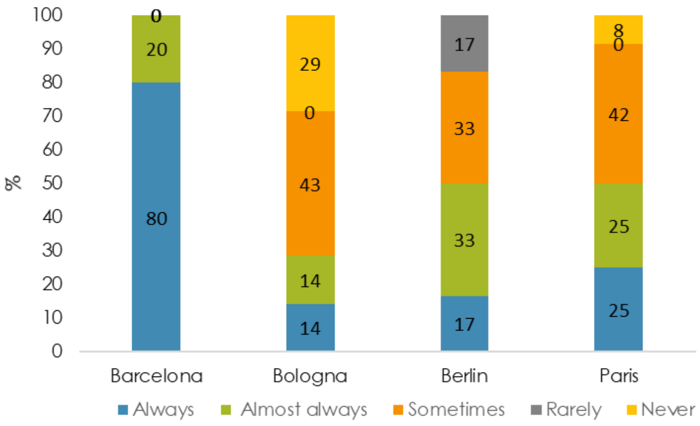
Supporting information 3.6. Barriers and the frequency with which they occur in four European cities RUA



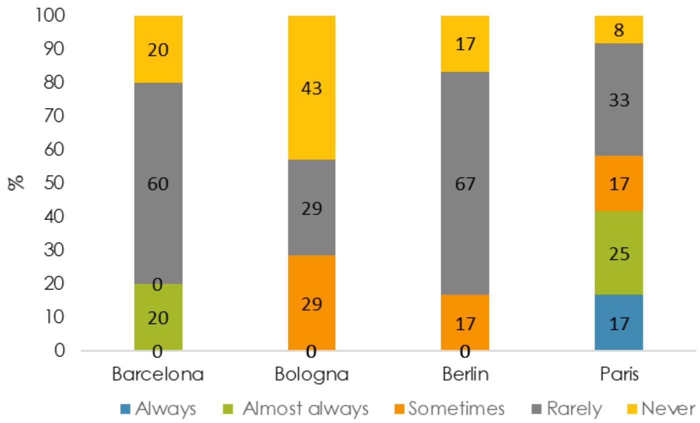
Architectural barriers and the frequency with which they occur from the stakeholder's perception from four European cities. (1) RUA is prohibited in existing buildings, (2) RUA is prohibited in historical buildings, (3) RUA is prohibited in all new buildings, (4) building code not considering RUA (legal lack), (5) RUA is allow with restrictions on the materials used, (6) RUA is allow conditioned to reinforced building structure, (7) building code prohibiting RUA due to sightlines visibility (from the rooftop to other buildings), (8) building code prohibiting RUA due to disturbance (noise, shadows, privacy), and (9) limits of building height hinder RUA.



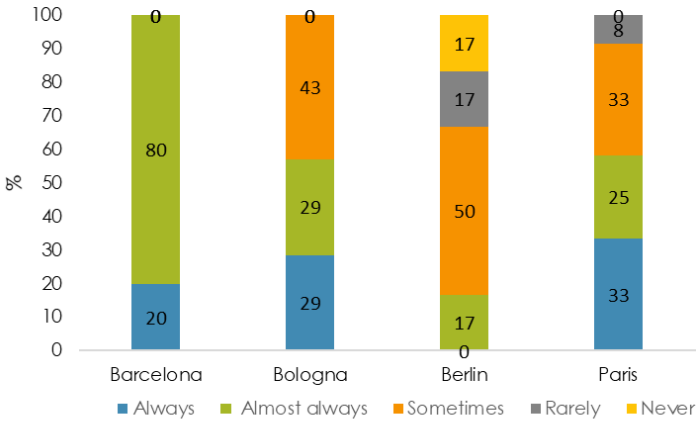
Frequency of the barrier: RUA is prohibited in existing buildings.



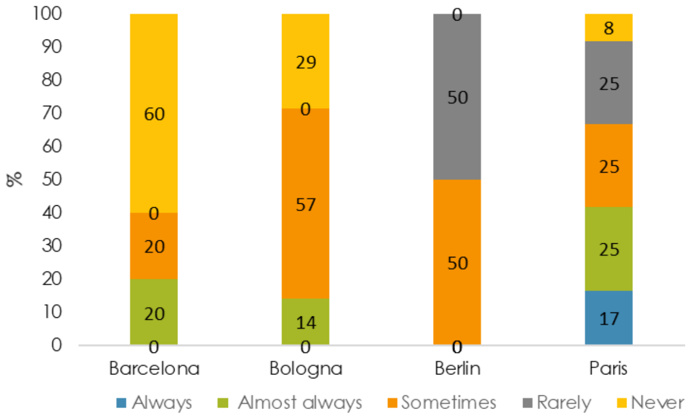
Frequency of the barrier: RUA is prohibited in historical buildings.



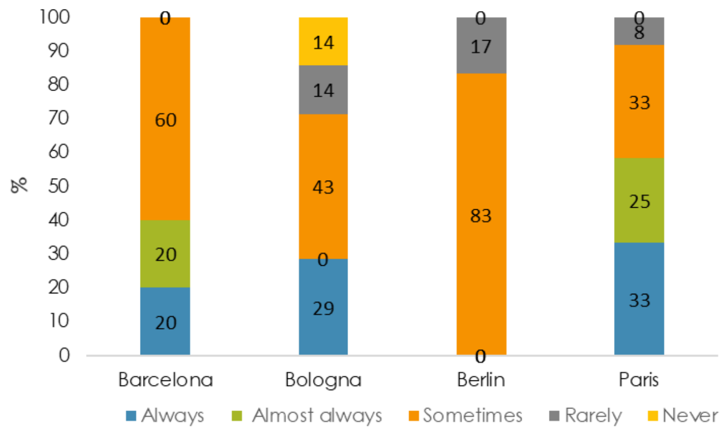
Frequency of the barrier: RUA is prohibited in in all new buildings.



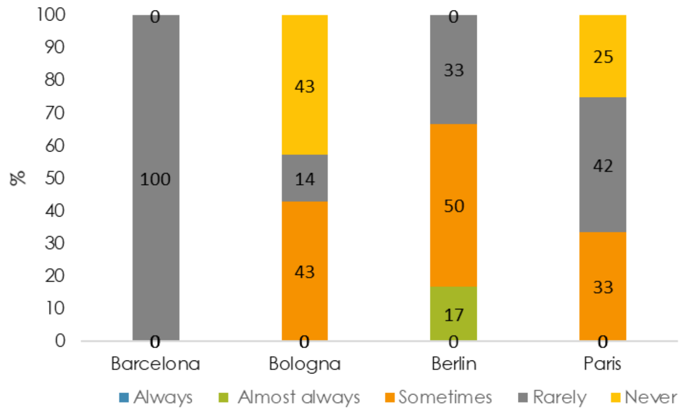
Frequency of the barrier: building code not considering RUA (legal lack).



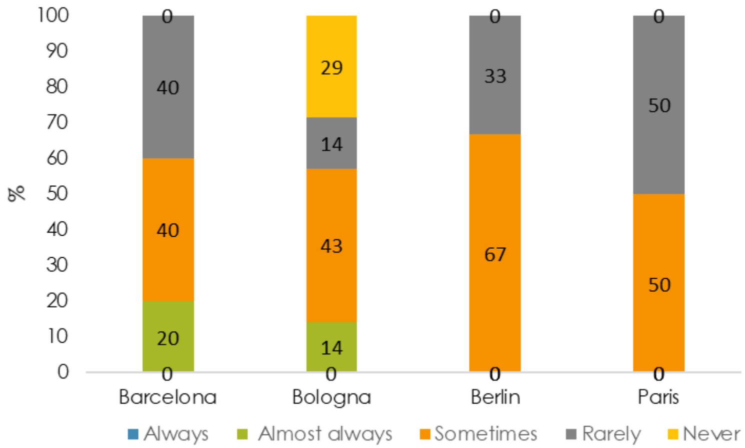
Frequency of the barrier: RUA is allow with restrictions on materials used.



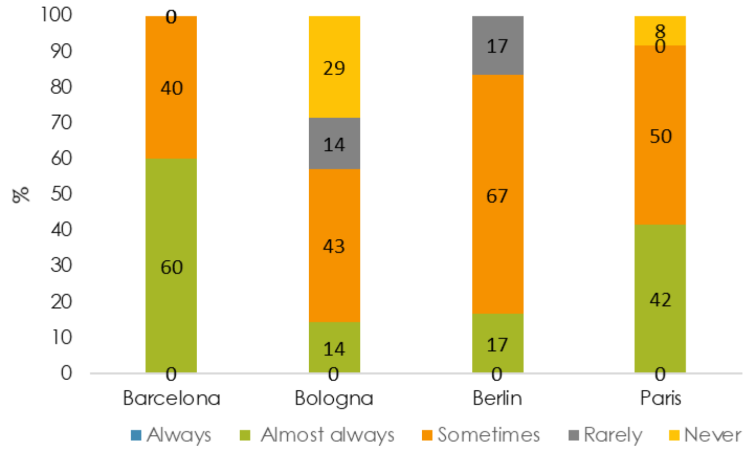
Frequency of the barrier: RUA is allow conditioned to a reinforce building structure.



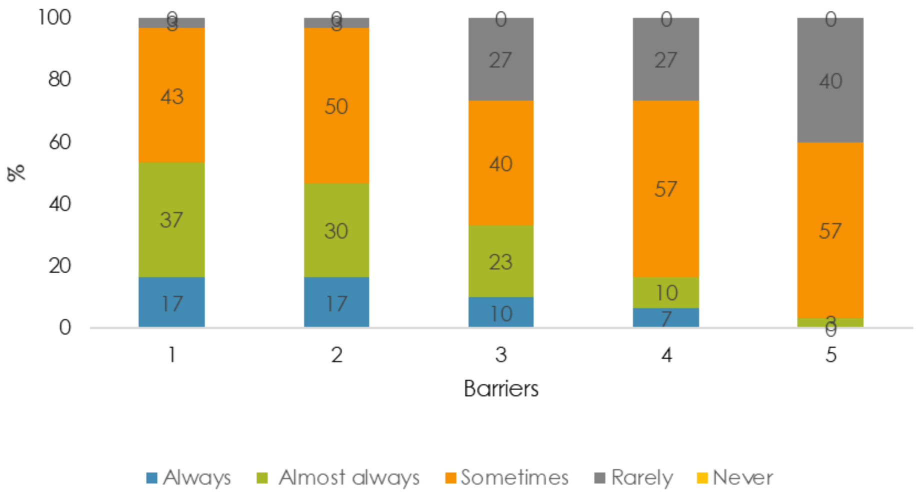
Frequency of the barrier: building code prohibiting RUA due to sightlines visibility (from the rooftop to other buildings).

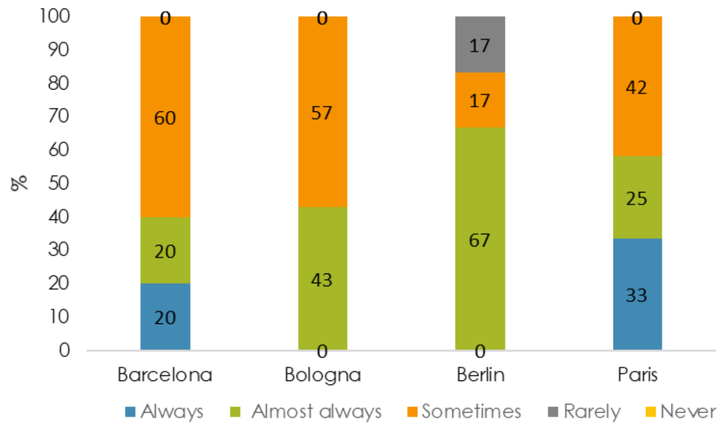


Frequency of the barrier: building code prohibiting RUA due to disturbance (noise, shadows, privacy).



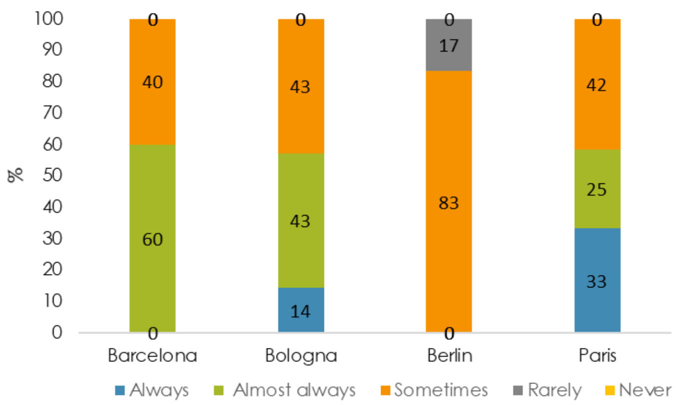
Frequency of the barrier: limits of building height hinder RUA.



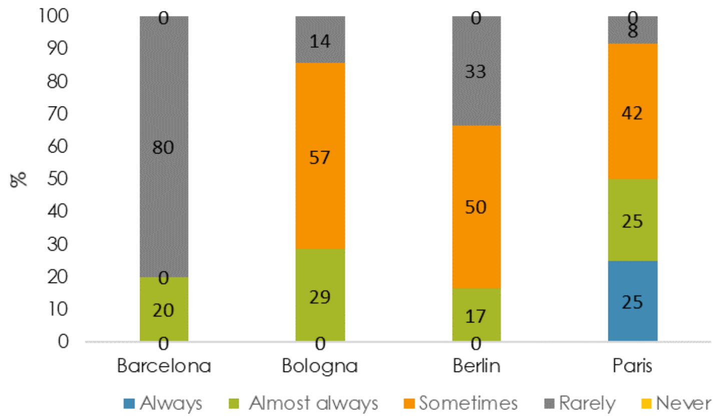


Technical barriers and the frequency with which they occur from the stakeholder's perception from four European cities. (1) Building design hinders logistics to operate RUA, (2) building design hinders roof accessibility, (3) rooftop slope hinders RUA, (4) rooftop material hinders RUA, and (5) competition of the use of roof hinders RUA.

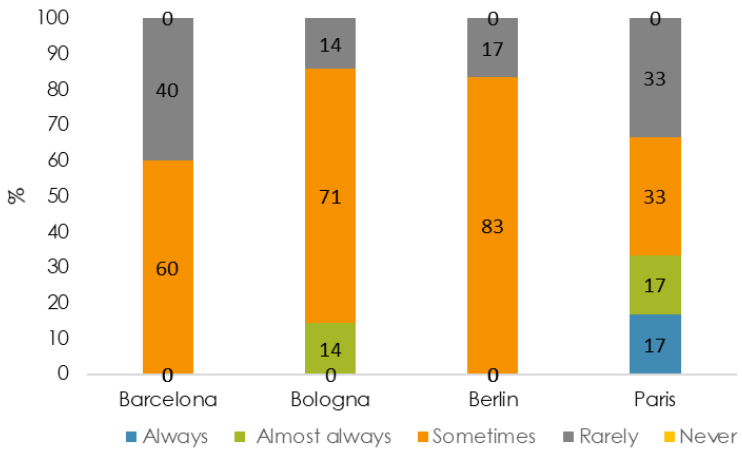
Frequency of the barrier: building design hinders logistics to operate RUA.



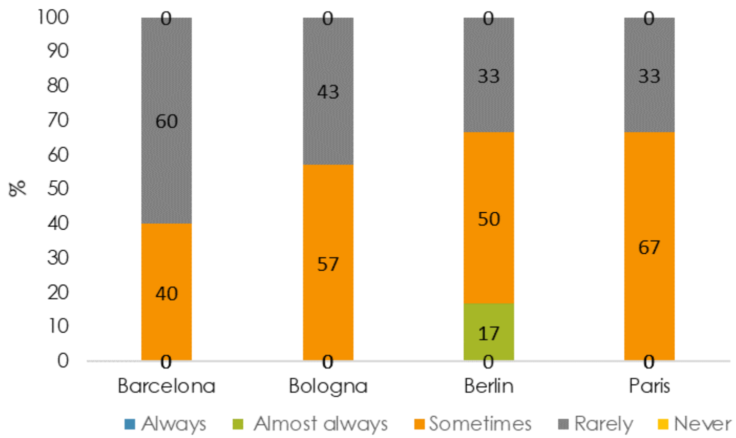
Frequency of the barrier: building design hinders roofs accessibility.



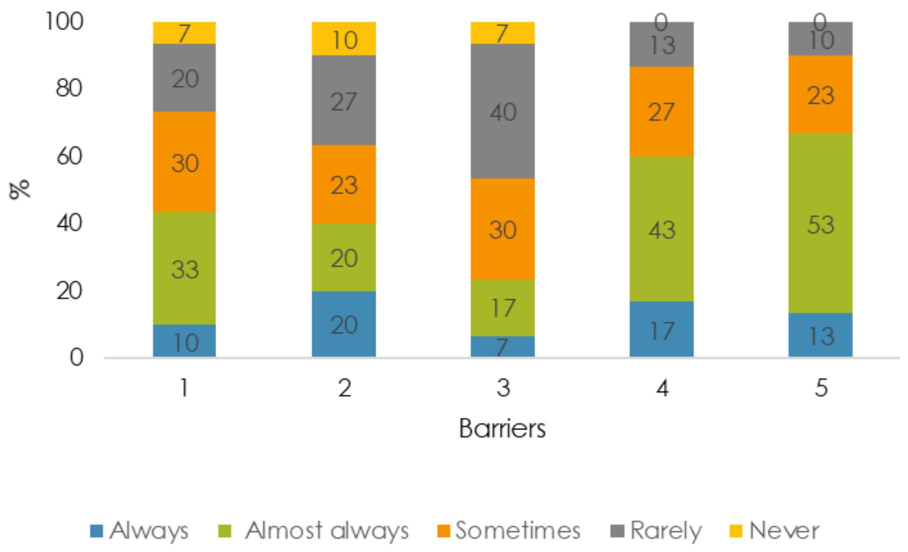
Frequency of the barrier: rooftop slope hinders RUA.



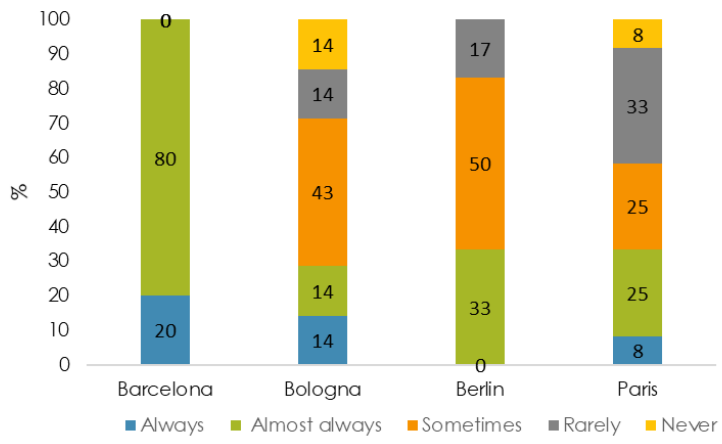
Frequency of the barrier: rooftop material hinders RUA.



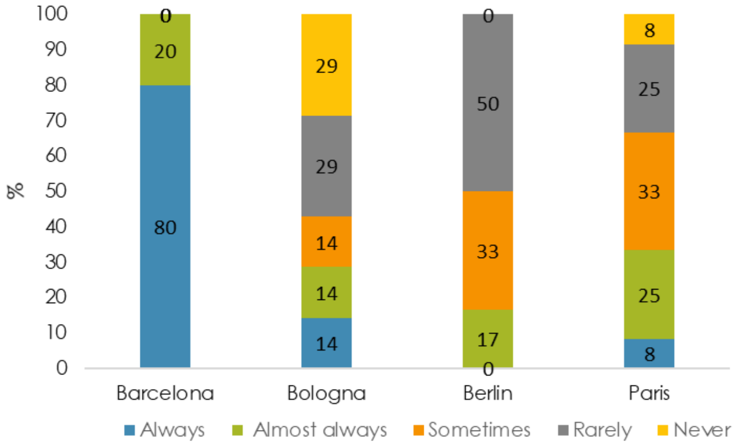
Frequency of the barrier: competition of the use of roof hinders RUA.



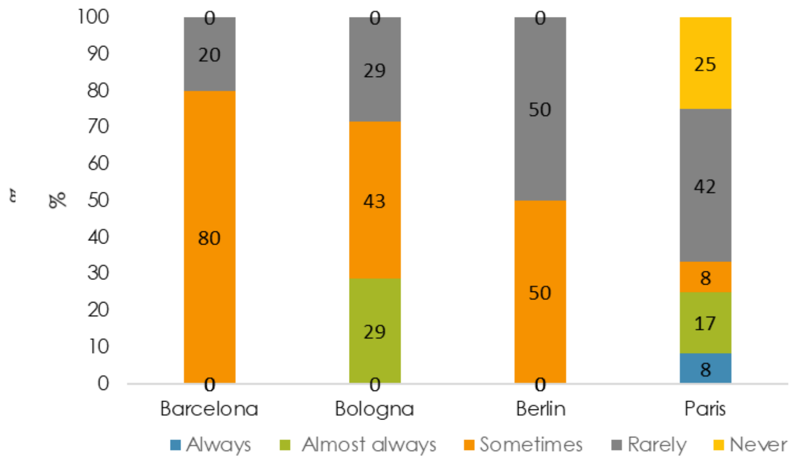
Economic barriers and the frequency with which they occur from the stakeholder's perception from four European cities. (1) Policies prohibit food sales, (2) policies prohibit food free distribution, (3) lack of legislation for sales food harvest on rooftops, (4) rooftop agriculture is not profitable, and (5) high cost of infrastructure hinder RUA.



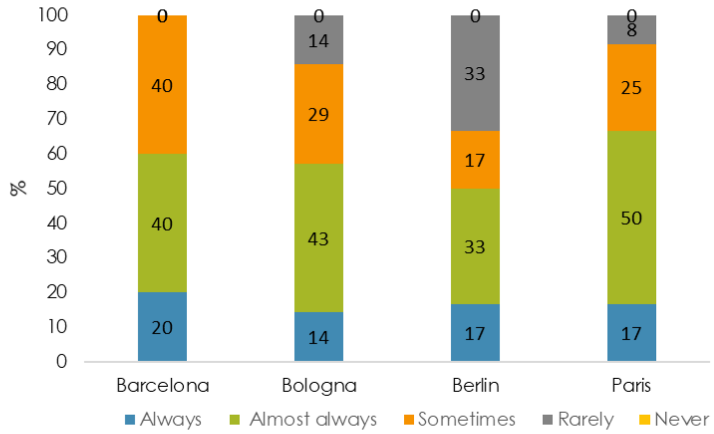
Frequency of the barrier: policies prohibit food sales.



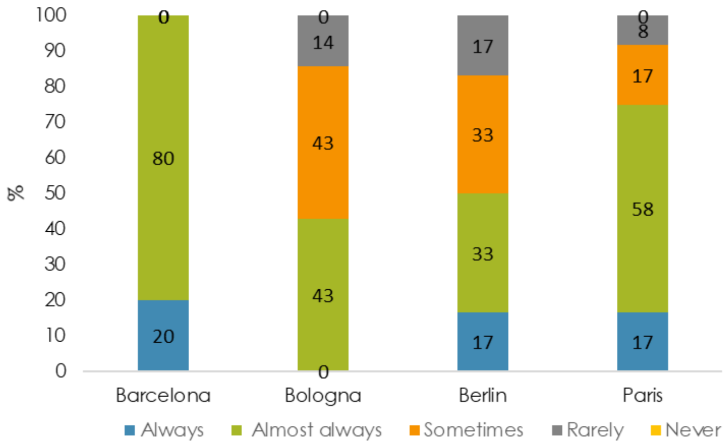
Frequency of the barrier: policies prohibit food free distribution.



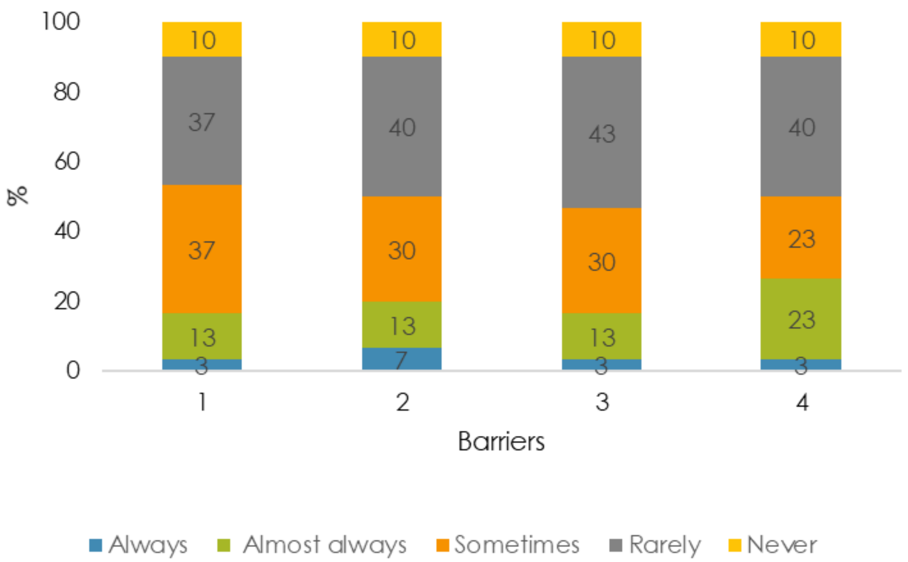
Frequency of the barrier: there is a lack of law for sales food harvest on rooftops.



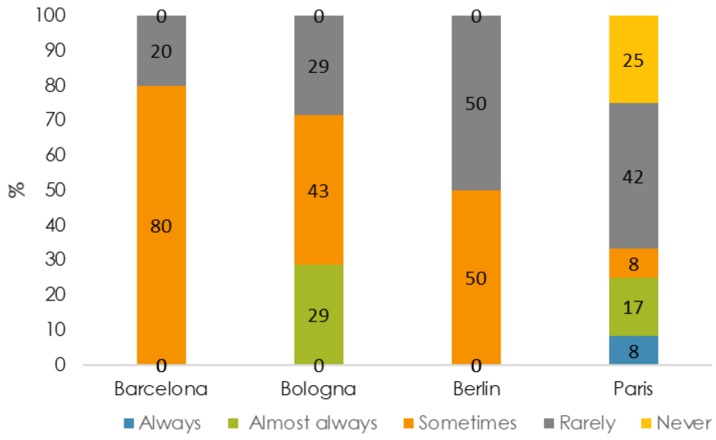
Frequency of the barrier: rooftop agriculture is not profitable.



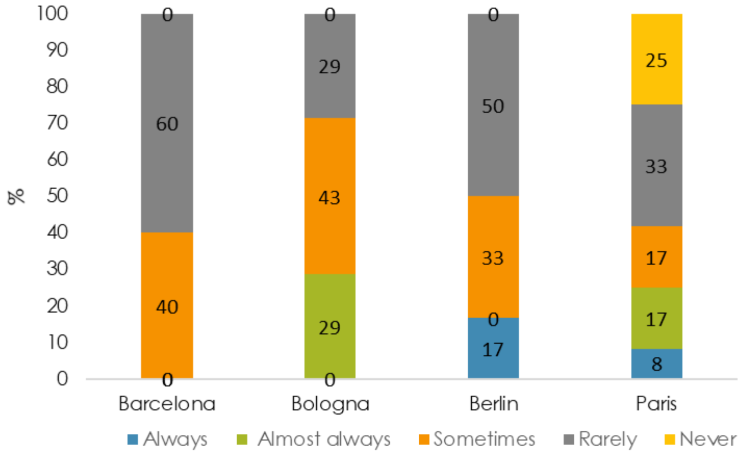
Frequency of the barrier: high cost of infrastructure hinder RUA.



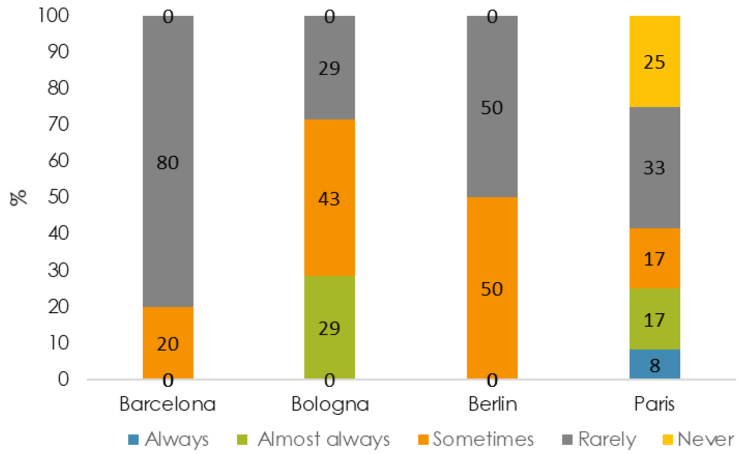
Social barriers and the frequency with which they occur from the stakeholder's perception from four European cities. (1) Residents do not want rooftop agriculture in their building, (2) lack of interest of the society, (3) exclusive access to rooftop food and projects, and (4) consumers lack acceptance of rooftop food production.



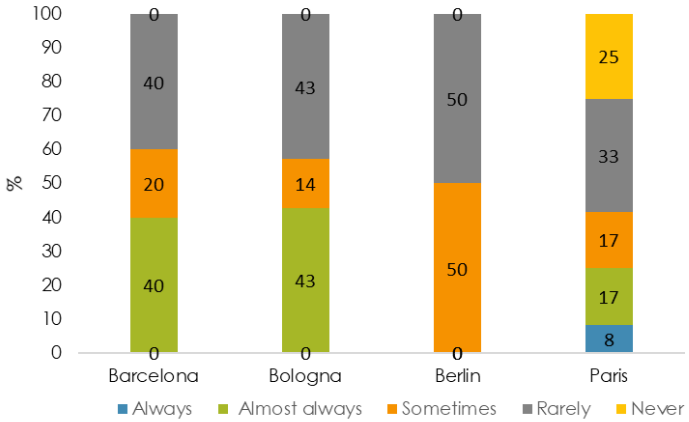
Frequency of the barrier: residents do not want rooftop agriculture in their building.



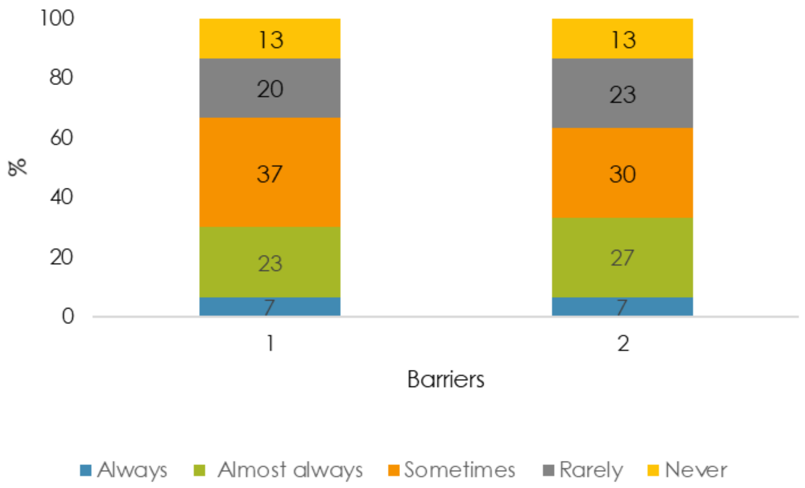
Frequency of the barrier: lack of interest of the society.



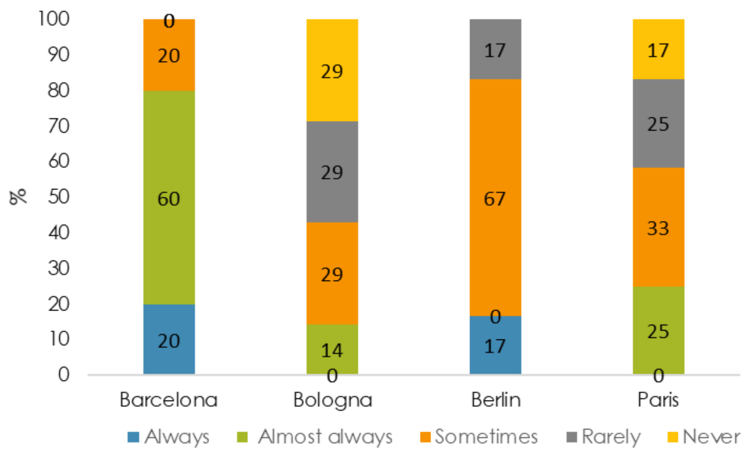
Frequency of the barrier: exclusive access to rooftop food and projects.



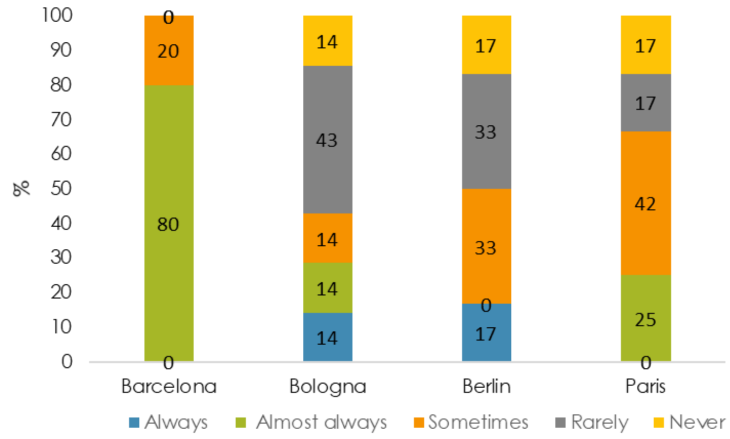
Frequency of the barrier: consumers lack acceptance of rooftop food production.



Urban planning barriers and the frequency with which they occur from the stakeholder's perception from four European cities. (1) Urban planning zoning ordinance prohibits agricultural land use in the city and (2) there is a legal lack regarding agricultural land use in the city.



Frequency of the barrier: urban planning zoning ordinance prohibits agricultural land use in the city.



Frequency of the barrier: there is a legal lack regarding agricultural land use in the city.

Appendix 4. Supporting information for chapter 7

Perceptions on barriers and opportunities for integrating urban agri-green roofs: a European Mediterranean compact city case

Supporting information 4.1. Barriers support list for the World

Category	Barriers
Economic	Project cost
Economic	Previous structural inform cost
Economic	Waterproofing cost
Economic	Maintenance cost
Technological/architectural	UAGR are not well identified in material banks or BIM energy-type calculation programs
Technological/architectural	Need to expand sanitation network
Technological/architectural	Lack of database regarding constructive components of UAGR
Technological/architectural	Difficulties regarding water use: collection and storage
Technological/architectural	Urban limitation to perimeter adjustment
Technological/architectural	Some buildings need structural reinforcement
Technological/architectural	Difficulties of access and insulation of roofs
Technological/architectural	Possible pathologies due to poor execution (humidity/structure)
Social	Need for a community leader
Social	Self-management problems regarding long-term maintenance
Social	Perception of technical problems associated with UAGR
Social	Perception of inequality of benefits
Social	Lack of community implication
Social	Low solidarity among neighbors, difficult consensus
Social	Stakeholders complexity when projecting (tenants, owners)
Social	Skepticism regarding community benefits of UAGR)
Legal/administrative	Lack of specific normative regarding UAGR
Legal/administrative	Need to modify the statutes of neighboring communities
Legal/administrative	Limitation of pergolas/greenhouses by volume issues
Legal/administrative	You cannot sell agricultural products

Legal/administrative	Current legislation focuses more on UAGR promotion rather than agricultural production
Legal/administrative	A majority of 50% is necessary to carry out UAGR project, and more in case of reinforcement needs.
Legal/administrative	Lack of unified criteria by the public administrations
Legal/administrative	Financial aids require to suspend rental agreements
Environmental	Limitation of water resources during drought periods
Environmental	Environmental impacts of the construction of greenhouses, solar panels…

Supporting information 4.2. Opportunities support list for the World Café

Category	Opportunities
Economic	Recovery of underused spaces
Economic	Energy savings due to better insulation
Economic	Complement the "shopping lists" with self-produced products
Economic	Reduction of sewerage tax
Economic	New jobs creation
Economic	Product consumption cooperatives
Technological/architectural	Urban landscape improvement
Technological/architectural	Integration of the UAGR in the building design
Technological/architectural	Buildings more isolated (thermic and acoustic)
Technological/architectural	Fluxes synergy (heat, ventilation, water and organic matter)
Technological/architectural	Possibility of obtaining environmental, energetic and food indicators.
Technological/architectural	Reuse of nutrients from the residual water flows of the crops (circular fluxes).
Technological/architectural	Incorporation of ICT (information and communication technologies) to the management of UAGR
Technological/architectural	Smart buildings
Social	Boost health spaces
Social	Improve corporate social responsibility by introducing UAGR in corporate buildings

Social	Promotion of nature-related activities
Social	Most self-sufficient cities
Social	Facilitates social inclusion
Social	Urban farming (collective inclusion)
Social	Variety of fresh seasonal products
Legal/administrative	Improvement and/or update of existing regulations
Legal/administrative	New metabolic vision of the city
Legal/administrative	Meet the city's international agreements on food and climate change
Environmental	Biodiversity boost. Naturalization of the city.
Environmental	Heat island effect reduction.
Environmental	Take advantages of local endogenous resources (rainwater, sunlight, etc.)
Environmental	Reduction in CO_2 emissions (or equivalents)
Environmental	Reduction of sewer network flows
Environmental	Minimization of food waste in collection, transport, and storage.

Supporting information 4.3. Complete barriers and opportunities

Data extracted from the UAGR World Café. If an opportunity was unanimously identified among all the stakeholders of the same type, it is represented in dark grey. If the barrier was identified by some stakeholders but not all, it is noted in light grey. If the barrier was not identified by stakeholders, it appears blank. Stakeholders were public administration (PA), private companies (PC), research centers (RC), and owners and users (OU). Scale includes city (C), building (B), and global (G). Stage of UAGR life cycle comprises project (P), construction (C), and use (U).

Social Barriers	Relative weight on the total of answers (%) (m=110)	Stakeholders agreement (%) (n=24)	Public administration (PA)	Private companies (PC)	Research centers (RC)	Owners and users (OU)	Scale	Stage of UAGR life cycle
Lack of information and scope regarding UAGR	22	100	Dark grey	Dark grey	Dark grey	Dark grey	C	P
Lack of social cohesion	22	100	Dark grey	Dark grey	Dark grey	Dark grey	B	P
Use of UAGR by communities	16	75	Light grey	Light grey	Light grey	Light grey	B	U
Maintenance or unforeseen issues	10	46	Light grey	Light grey	Light grey	Light grey	B	U
Difficulties regarding decision-making	8	38	Light grey	Light grey	Light grey	Light grey	B	P
Lack of examples by municipalities and administrations	6	29	Light grey	Light grey	Light grey	Light grey	C	P
Age bands of interest regarding UAGR	5	20	Light grey	Light grey		Light grey	C	U
Administrators role	5	25		Light grey		Light grey	B	U
Compensation for the made efforts	2	8		Light grey		Light grey	G	U
Lack of technical reference for the communities	1	4	Light grey				B	P

Administrative barriers that appear once the social ones have been overcome	1	4					C	P
Lack of tracking	1	4					C	P
Robbery	1	4					C	U

Social opportunities	**Relative weight on the total of answers (%) (m=117)**	**Stakeholders agreement (%) (n=19)**	**Public administration (PA)**	**Private companies (PC)**	**Research centers (RC)**	**Owners and users (OU)**	**Scale**	**Stage of UAGR life cycle**
Social cohesion	16	100					B	U
Generate common spaces	11	68					B	U
Education tool	11	68					C	U
Generate "green + sociability" spaces	9	58					B	U
Food and local products appreciation	8	47					G	U
Community feeling	7	42					B	U
Social capital	7	42					G	U
Users' life quality	6	37					B	U
Therapeutic and pedagogic value (schools, geriatrics)	5	32					B	U
Dissemination of UAGR contest and projects	4	26					C	P
Facilitation of UAGR projects	3	16					C	P
Job creation	3	16					C	U

Out-of-market services	2	11	C	U
Opportunity for the elderly or mobility problems	2	11	C	U
Technicians tracking	1	5	C	P
City concept (landscape view)	1	5	C	U
Bring agricultural activities to the urban areas	1	5	C	U
Social slit reduction	1	5	C	U
Park “at your home"	1	5	B	U
Network of cameras to monitor UAGR	1	5	B	U
New business fields/market niches by administrators	1	5	C	U
“inhabit future”	1	5	C	U

Environmental barriers	Relative weight on the total of answers (%) (m=44)	Stakeholders agreement (%) (n=24)	Public administration (PA)	Private companies (PC)	Research centers (RC)	Owners and users (OU)	Scale	Stage of UAGR life cycle
Mediterranean clime	30	54	■	■	■	■	G	U
Technical or/and environmental lack of formation	16	29	■	■	■		B	P
Uses and quality of water	16	29	■	■	■	■	C	U
Water uses and quality	16	29	■	■	■	■	B	P
Materials used	11	21	■	■			B	U
Prejudices/problems regarding flora and fauna	11	21	■	■		■	B	U
Limitations of rainwater collections tanks	5	8		■		■	C	P
Lack of guidelines to carry out UAGR projects	2	4		■			G	P
Lack of an environmental/transdisciplinary concrete focus	2	4		■			C	U
Heat island effect	2	4		■			C	U
City pollution affecting productive crops	2	4		■	■		C	U
Conflicts of trees with height regulations	2	4				■	B	P

Environmental opportunities	**Relative weight on the total of answers (%) (m=55)**	**Stakeholders agreement (%) (n=19)**	**Public administration (PA)**	**Private companies (PC)**	**Research centers (RC)**	**Owners and users (OU)**	**Scale**	**Stage of UAGR life cycle**
Improved life quality	16	47	■	■		■	B	U
Biodiversity increase/improvement	11	32	■	■		■	C	U
Improved air quality	11	32	■	■		■	C	U
Better water uses	11	32	■	■			B	U
Environmental education	11	32	■	■		■	C	U
Run-off reduction	7	21		■	■	■	E	U
Decreasing in heat island effect	7	21	■	■		■	C	U
Improves in thermal insulation	7	21	■	■		■	E	U
Energy savings	6	16	■				E	U
Green corridors	6	16	■	■			C	U
Food sovereignty and proximity products	4	11	■			■	C	U
Climate change mitigation	2	5				■	G	U
Improves in acoustic insulation	2	5		■			E	U

Legal/administrative barriers	Relative weight on the total of answers (%) (m=74)	Stakeholders agreement (%) (n=24)	Public administration (PA)	Private companies (PC)	Research centers (RC)	Owners and users (OU)	Scale	Stage of UAGR life cycle
Lack of specific regulations and protocols	23	71					C	P
Volumetric limitations	18	54					B	P
Vertical property regulations	12	38					B	P
Commercialization of the obtained products	11	33					C	P
District legal frameworks	11	33					C	P
Complexity of the required permissions/documentation	8	25					C	P
Regulations above the ordinances	4	13					C	P
Protection perimeter (safety standard height)	3	8					B	P
Legal insecurity of renewable energies	3	8					C	P
Impossibility of building new permanent structures	2	4					B	P
Licenses typologies	2	4					C	P
Protected tiled	2	4					C	C
Prohibition of cattle breeding on roofs	2	4					C	U
Little clarity in financial aids	2	4					C	P
Disconnection of urban and technical landscape	2	4					C	P

Legal/administrative opportunities	Relative weight on the total of answers (%) (m=48)	Stakeholders agreement (%) (n=19)	Public administration (PA)	Private companies (PC)	Research centers (RC)	Owners and users (OU)	Scale	Stage of UAGR life cycle
New specific regulations	31	79					C	P
Pilot projects promoted by the city council	15	37					C	P
Creation of an UAGR ecological certificate	13	32					C	P
Tax incentives	10	26					C	P
Contact other European cities/councils	8	21					G	P
Decriminalization/facilitation of marketing urban agricultural products	6	16					C	U
Subjects in architectural schools	4	11					G	P
New community agreements	4	11					B	P
"rain + green"	4	11					B	U
Prioritize certain social groups for UAGR projects	2	5					C	U

Allow economic activities on the roofs	2	5					C	U

Economic barriers	Relative weight on the total of answers (%) (m=25)	Stakeholders agreement (%) (n=22)	Public administration (PA)	Private companies (PC)	Research centers (RC)	Owners and users (OU)	Scale	Stage of UAGR life cycle
Initial investment	40	46					B	P
Small benefit perception	20	23					B	P
Maintenance costs	20	23					B	U
Lack of financial aids	12	14					C	P
Very expensive for public administrations	4	5					C	P
Difficulties on marketing the product	4	5					C	U

Economic opportunities	Relative weight on the total of answers (%) (m=37)	Stakeholders agreement (%) (n=18)	Public administration (PA)	Private companies (PC)	Research centers (RC)	Owners and users (OU)	Scale	Stage of UAGR life cycle
Profits derived from the UAGR	32	67					B	U
Added value to building	15	28					B	U
New jobs and business	11	22					C	U
Sales of local products	11	22					C	U
Tax incentives	11	22					C	P
Energetic and economic opportunity	5	11					B	U
Prevention in public health	5	11					C	U
Consumer-housing-office cooperatives	3	6					G	U
Indirect economic profits derived from social benefits	3	6					B	U
Changes in legal frameworks	3	6					C	P
Environmental regulations on a business level	3	6					G	U

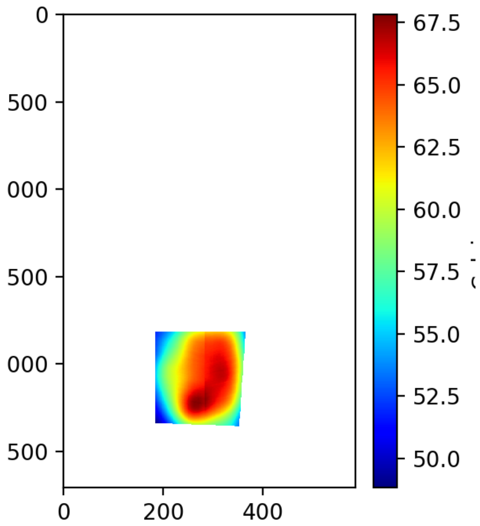
Technological/architectural barriers	Relative weight on the total of answers (%) (m=64)	Stakeholders agreement (%) (n=24)	Public administration (PA)	Private companies (PC)	Research centers (RC)	Owners and users (OU)	Scale	Stage of UAGR life cycle
Pre-condition of the roof and its elements	23	63	■	■	■	■	B	P
Structural load limitations	22	58	■	■	■	■	B	P
UAGR accessibility	16	42	■	■		■	B	P
Safety on the roofs	9	25	■	■	■	■	B	P
Priority of aesthetic criteria versus sustainable practices	8	21		■	■	■	B	P
Material limitations	5	13	■	■			C	P
Installation of electricity and water network	5	13	■	■	■		B	C
Waterproof materials guarantee	3	8		■		■	G	C
Cost of waterproofing	3	8			■		B	P
Difficulty on place water tanks	2	4				■	B	C
Heritage limitations	2	4	■				B	P
Old buildings	2	4		■			B	P
Lack of specific materials for UAGR construction	2	4		■			G	C

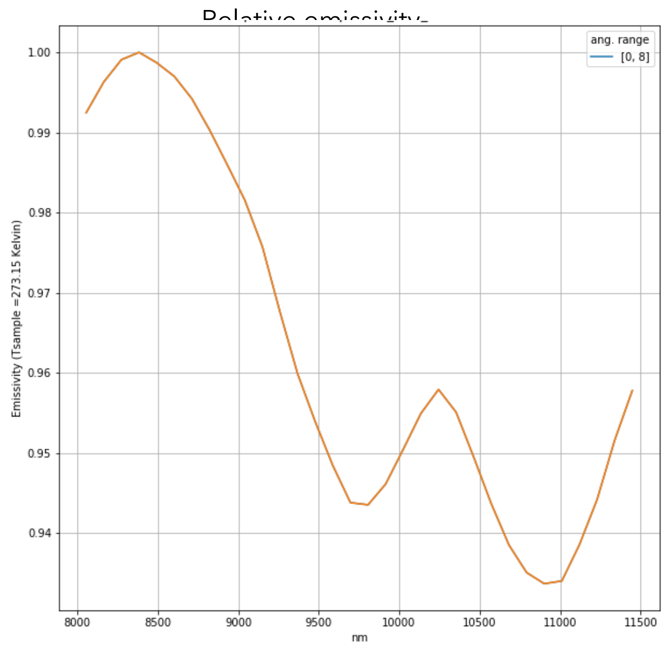
Technological/architectural opportunities	Relative weight on the total of answers (%) (m=40)	Stakeholders agreement (%) (n=19)	Public administration (PA)	Private companies (PC)	Research centers (RC)	Owners and users (OU)	Scale	Stage of UAGR life cycle
Aesthetic improvement	15	32					B	U
New space's uses	13	26					B	U
Update current facilities	13	26					B	U
Improvement in thermal and acoustic insulation	10	21					B	U
Creation of a common space to share experiences related with UAGR	10	21					C	U
Redistribution of roof elements	8	16					B	U
More sustainable cities and buildings	8	16					B	U
Opportunity for smart buildings	8	16					B	U
Network of technicians between different cities	5	11					C	U

Analyze climatic and environmental data	5	11					B	U
Waterproof improvement	3	5					B	U
Better city drainage	3	5					C	U
Opportunity to build green corridors	3	5					C	U

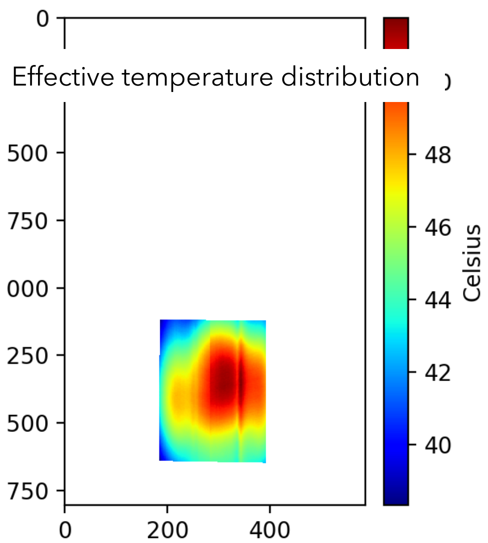
Appendix 5. Laboratory-based spectral data acquisition of roof materials using thermal infra-red sensor

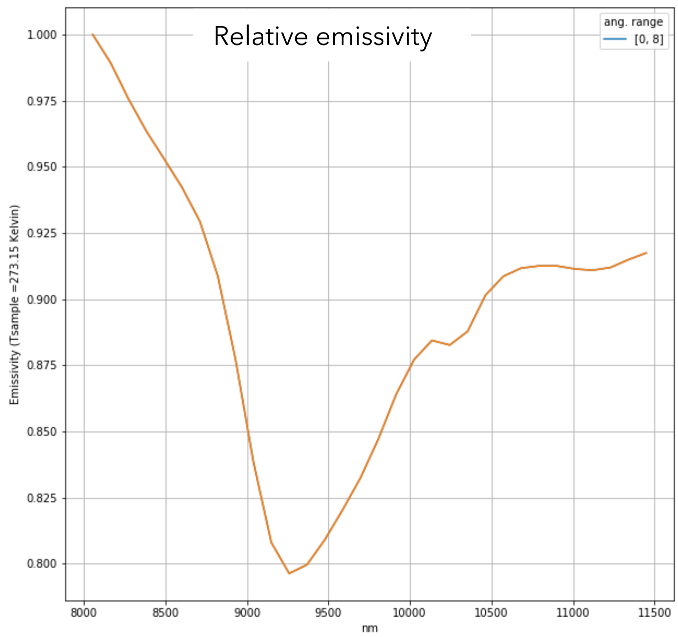
Ceramic tile, burnt red, dull (C01).



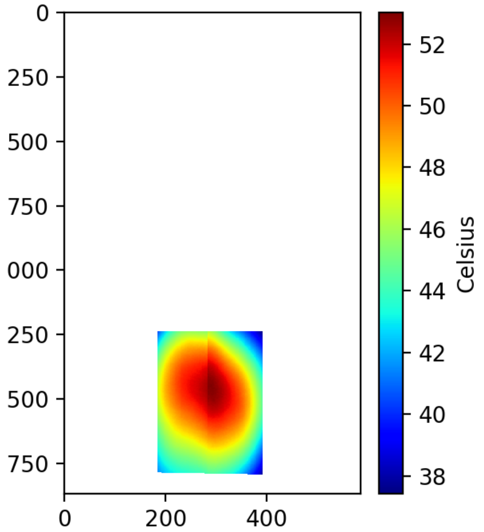


Ceramic gres porcelain tiles, white, shiny (C02).

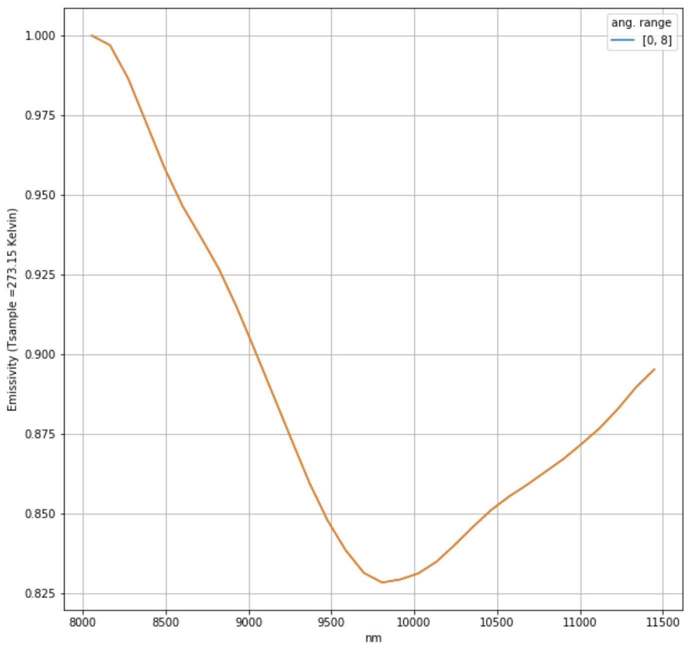




Ceramic gres porcelain tiles, red (C03).

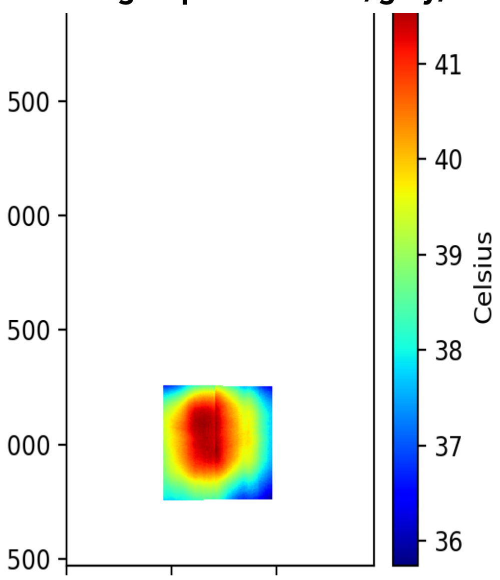


Effective temperature distribution

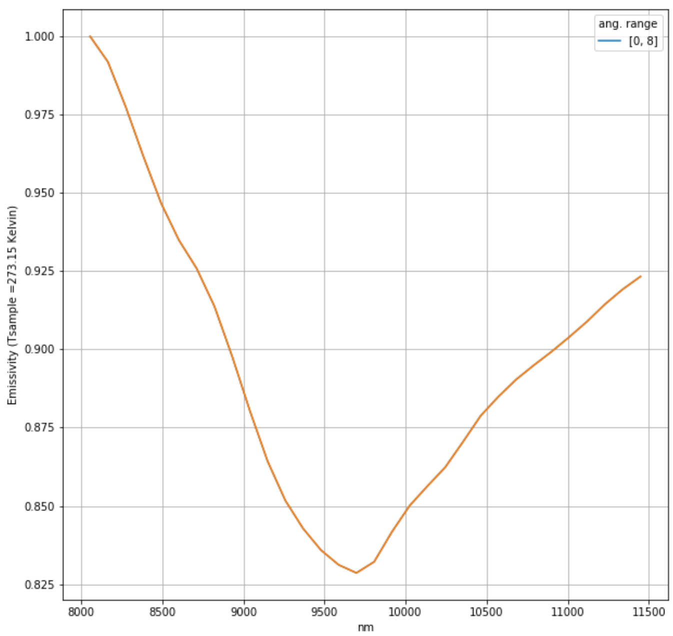


Relative emissivity

Ceramic gres porcelain tiles, grey, dull (C04).

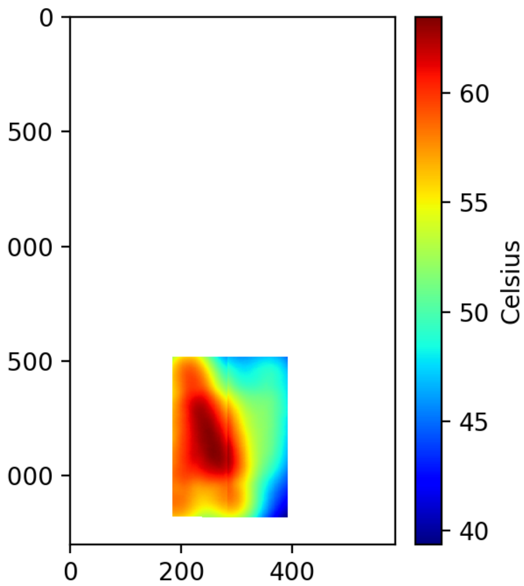


Effective temperature distribution

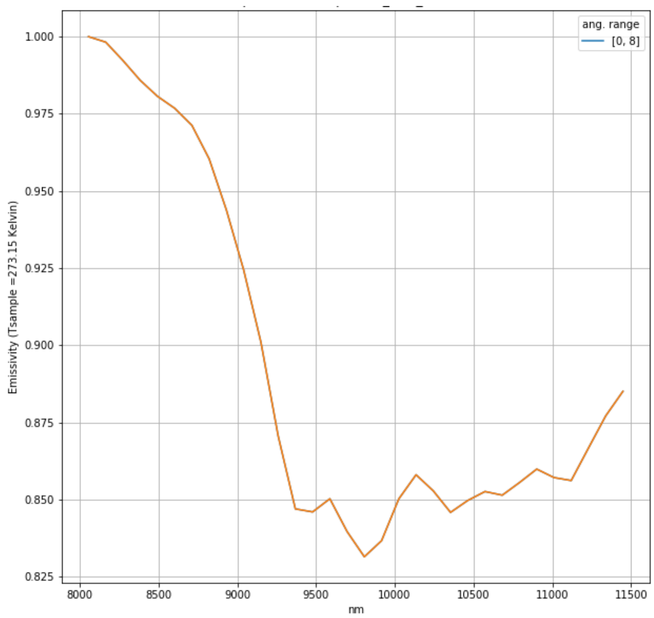


Relative emissivity

Ceramic gres porcelain tiles, multicoloured burnt red/brown/dark green, dull (C05).

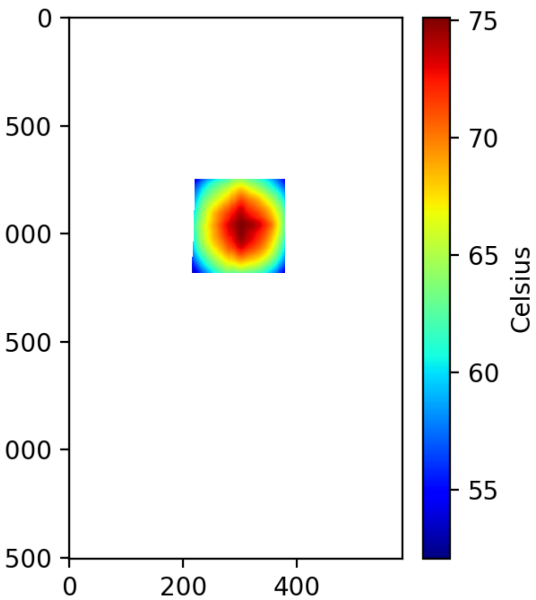


Effective temperature distribution

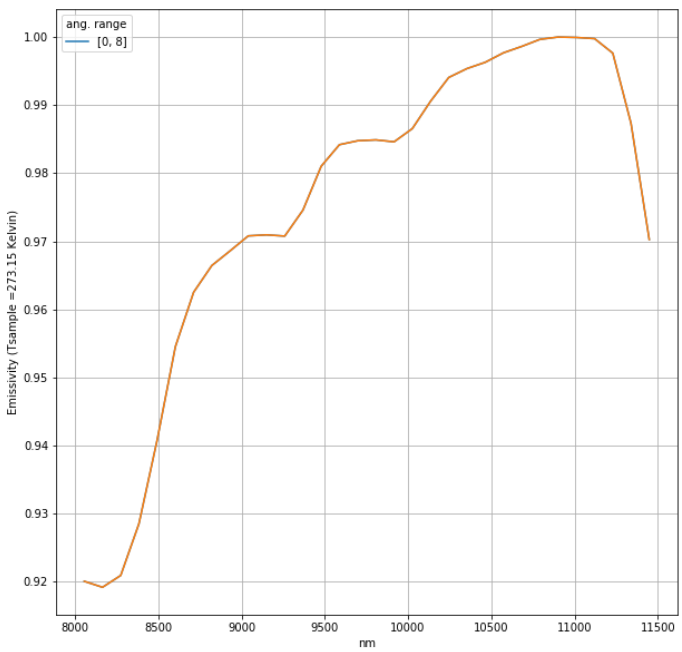


Relative emissivity

Concrete tiles, grey, dull (T01).

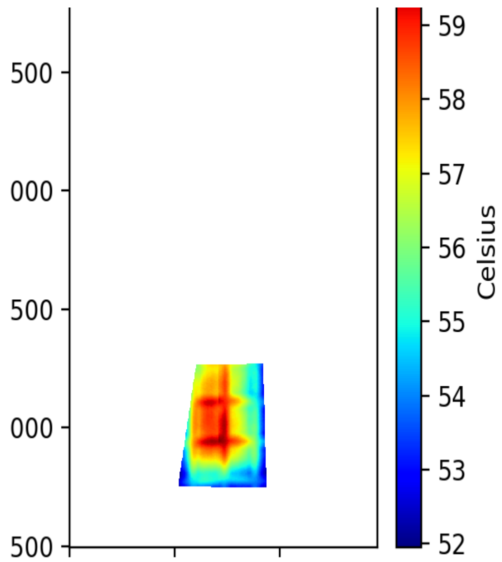


Effective temperature distribution

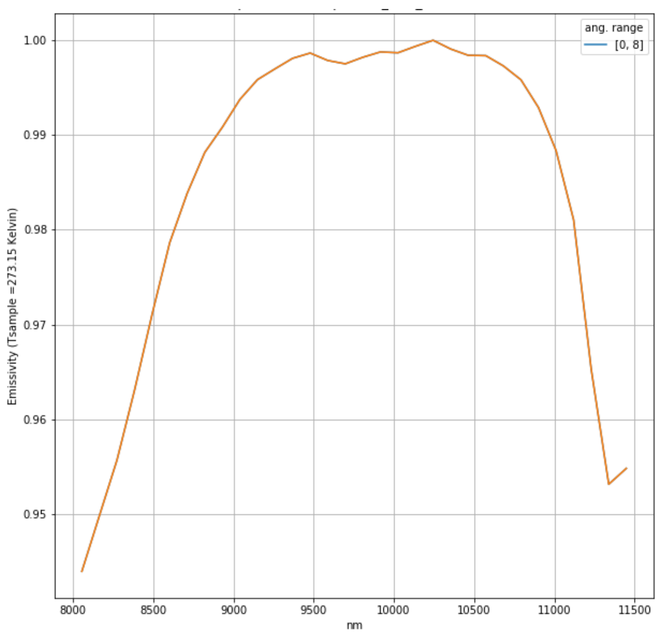


Relative emissivity

Concrete tiles, grey, dull (T02).

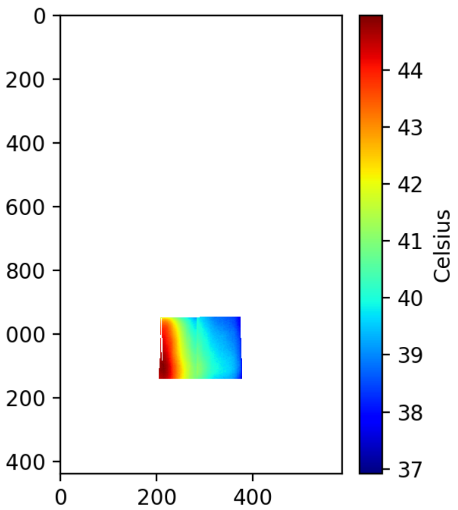


Effective temperature distribution

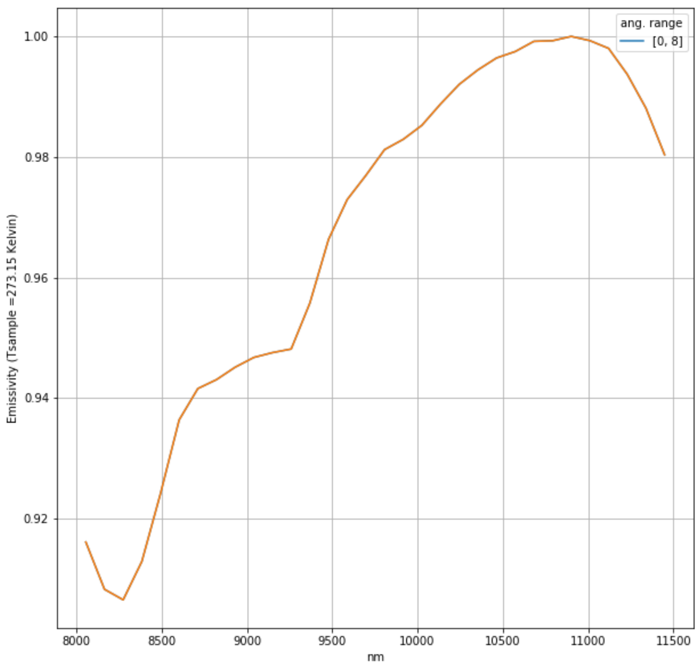


Relative emissivity

Concrete bricks, grey, dull (T03).

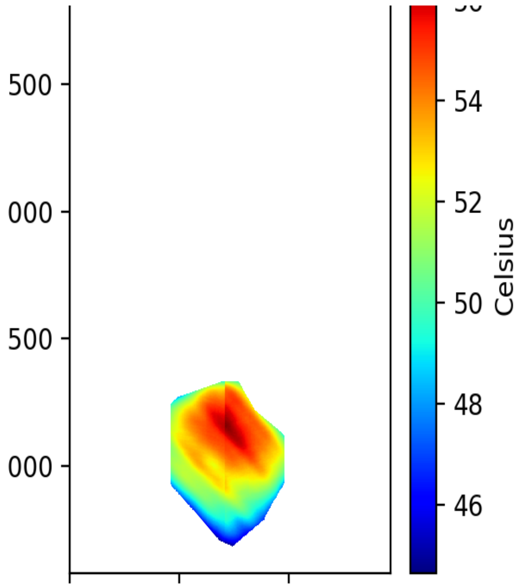


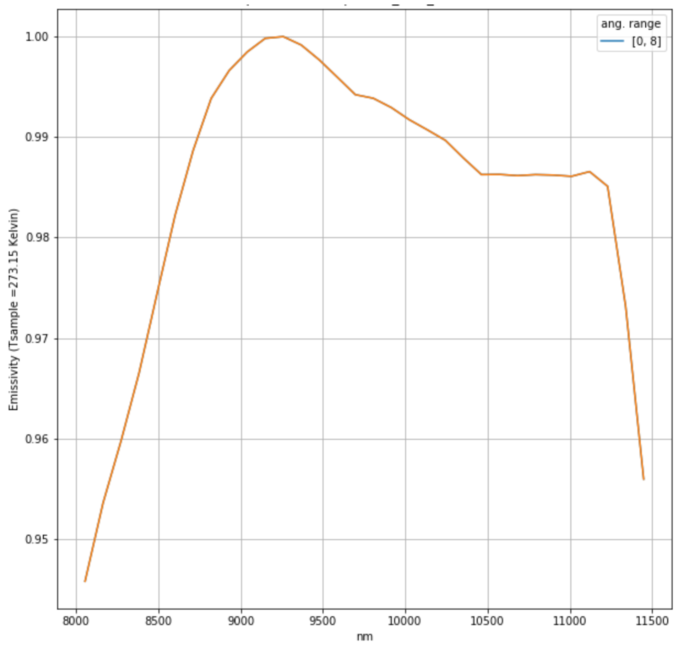
Effective temperature distribution



Relative emissivity

Cement corrugated fibre, grey, dull (T04).

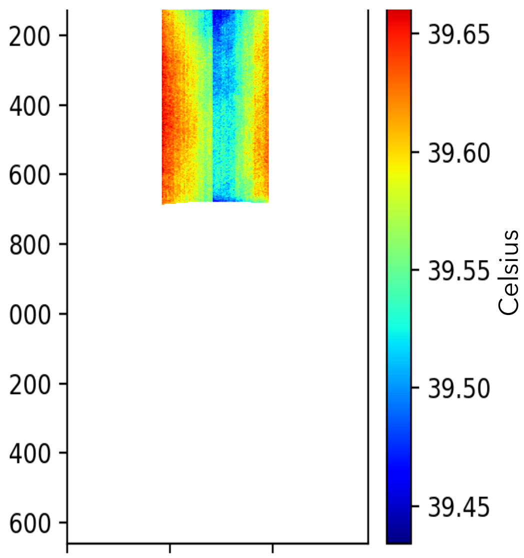


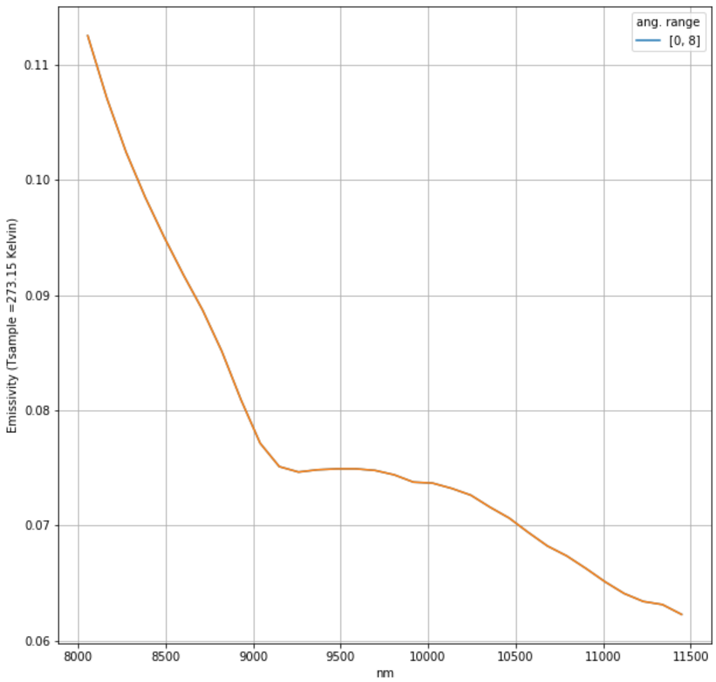


Effective temperature distribution

Relative emissivity

Metal steel shingles, grey, dull (M01).

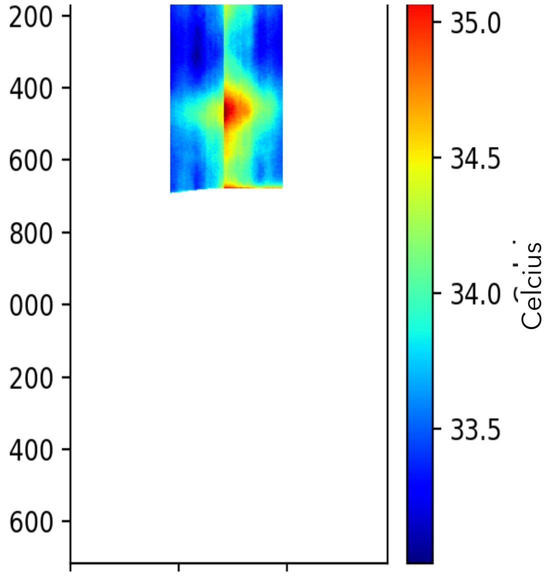




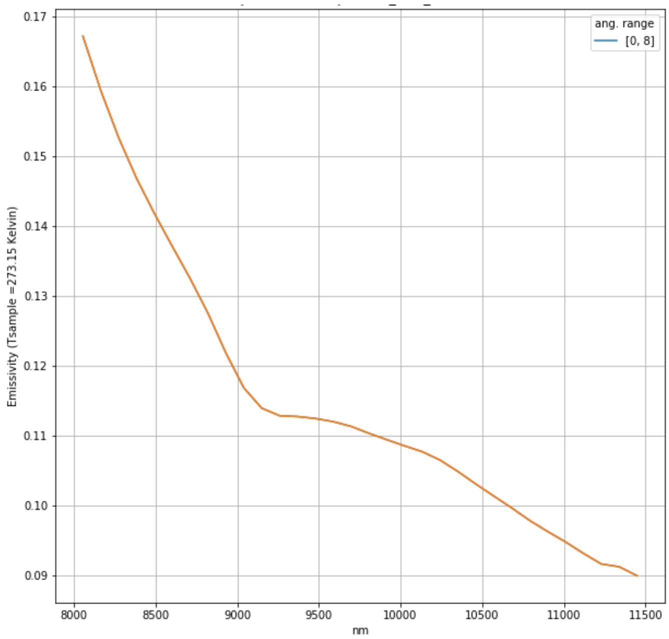
Effective temperature distribution

Relative emissivity

Metal galvanized steel shingles, grey, shiny (M02).

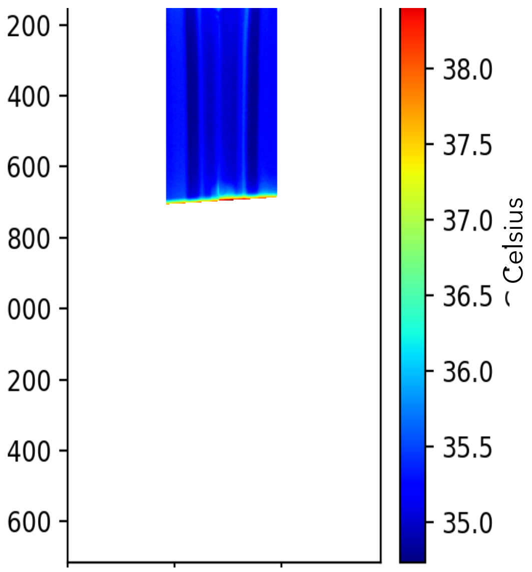


Effective temperature distribution

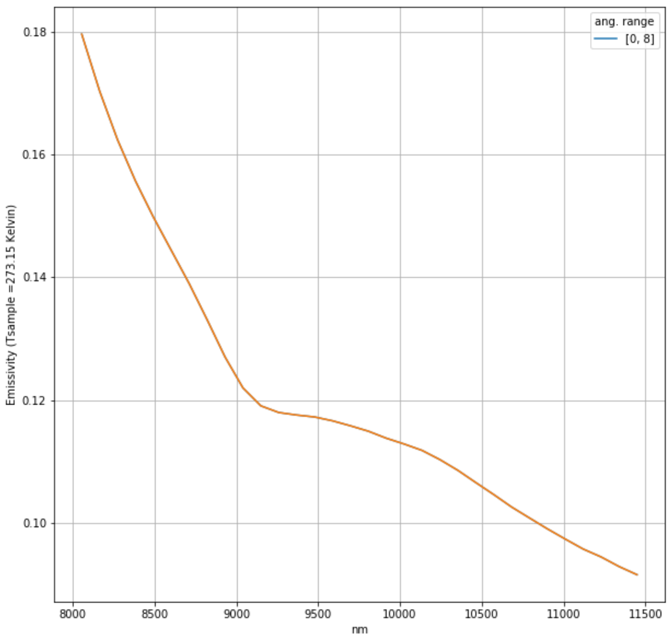


Relative emissivity

Metal inox steel shingles, grey, shiny (M03).

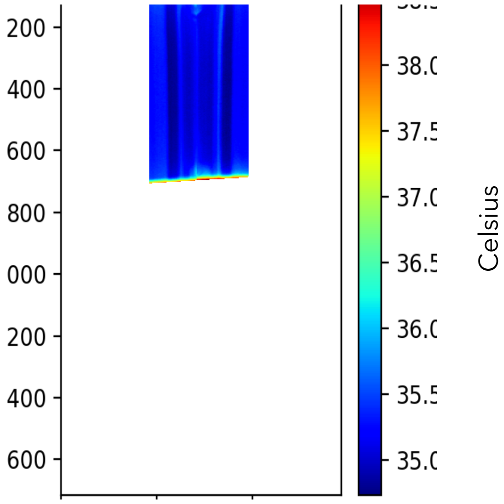


Effective temperature distribution

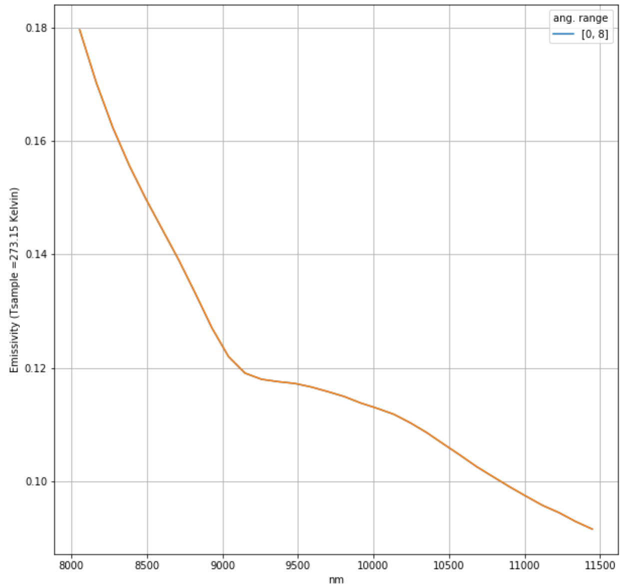


Relative emissivity

Metal aluminium shingles, grey, polished (M04).

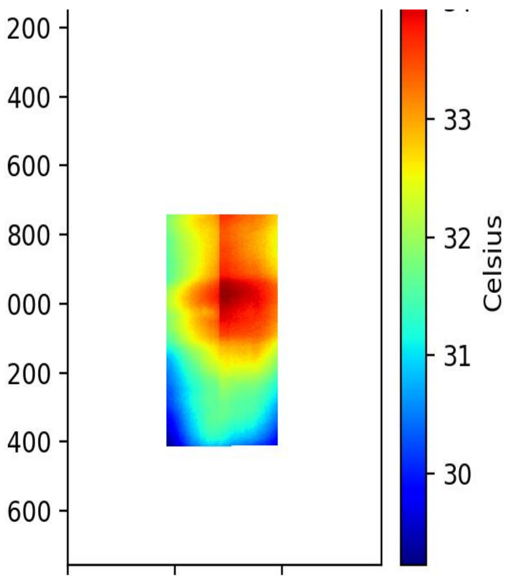


Effective temperature distribution

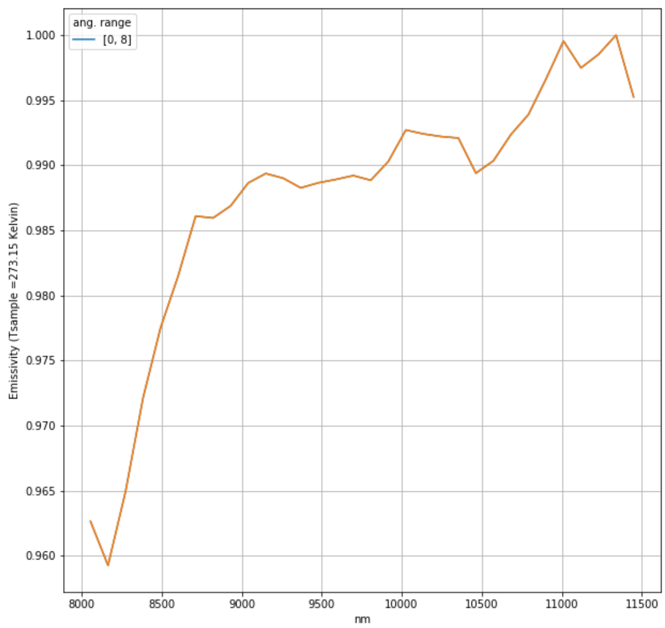


Relative emissivity

Metal steel shingles with paint beige (M05).

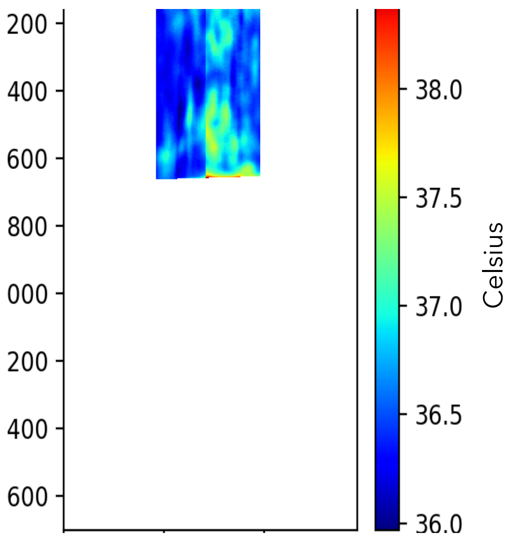


Effective temperature distribution

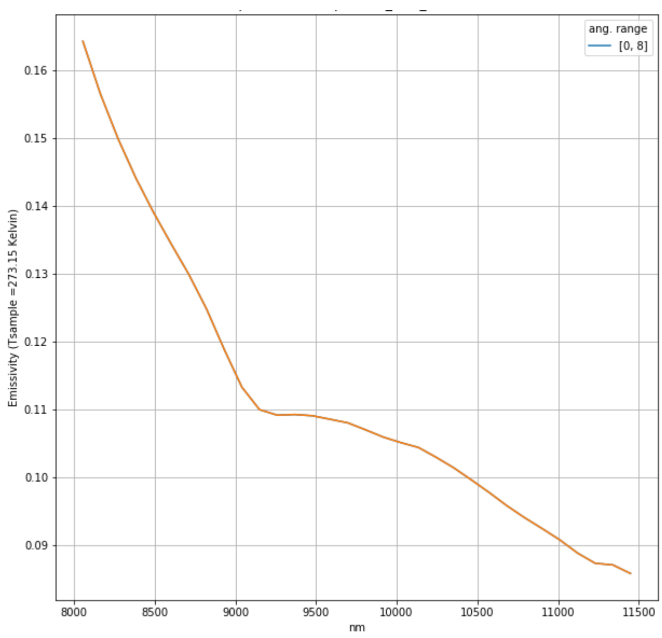


Relative emissivity

Metal copper shingles (M06).

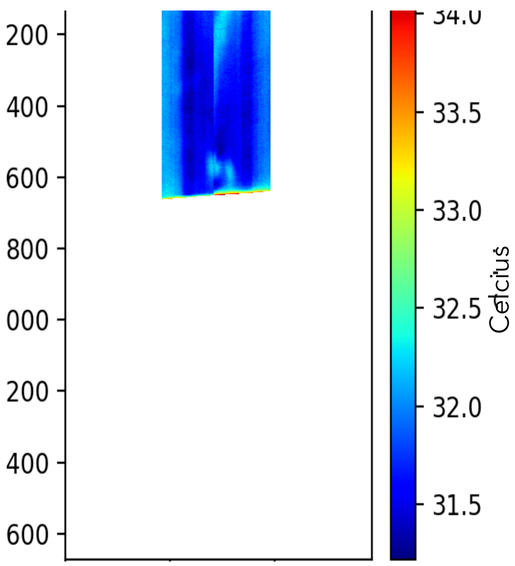


Effective temperature distribution

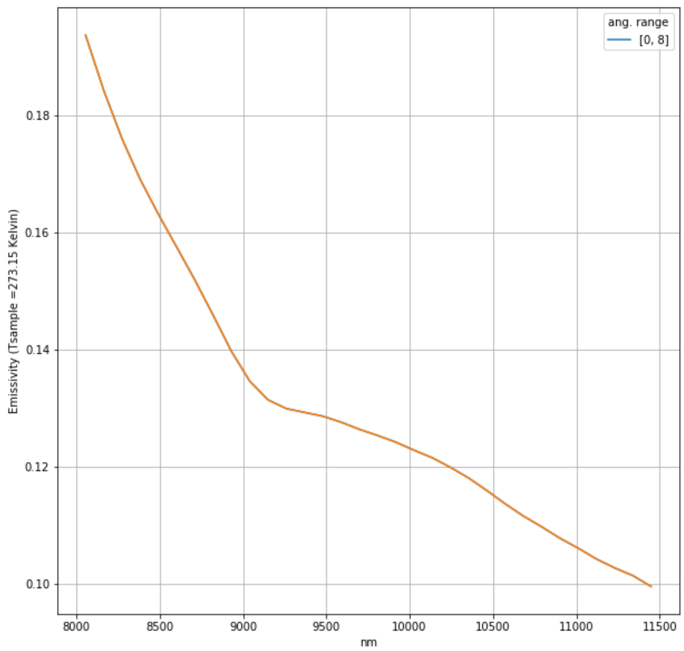


Relative emissivity

Metal zinc shingles, grey (M07).

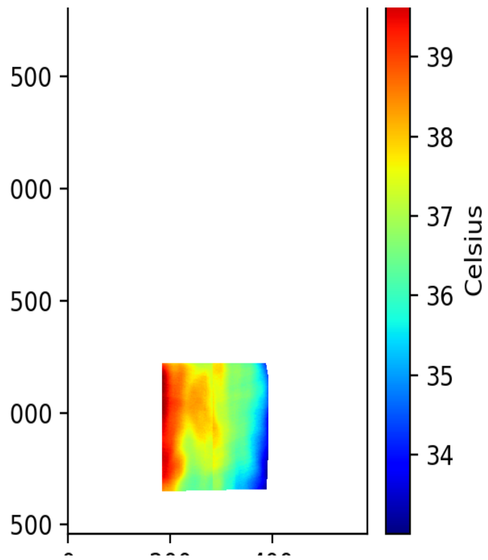


Effective temperature distribution

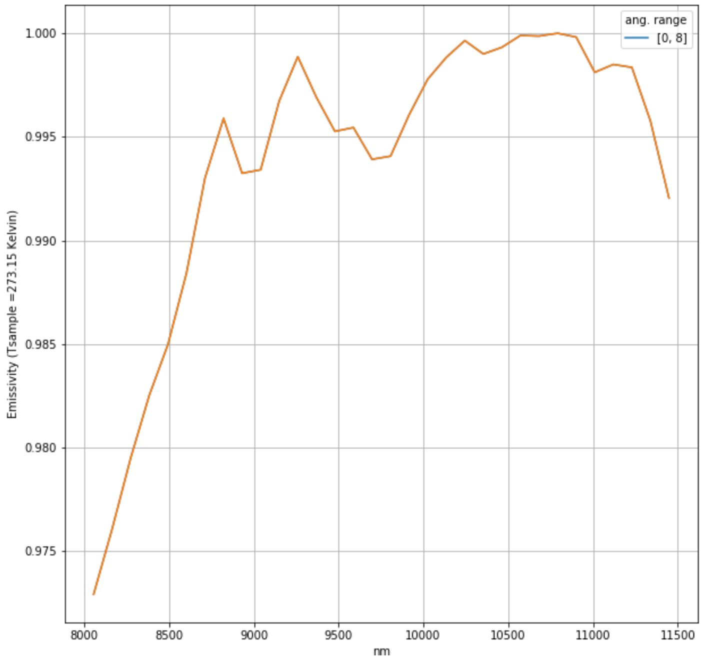


Relative emissivity

Shingles with blue paint, synthetic enamel (PT01).

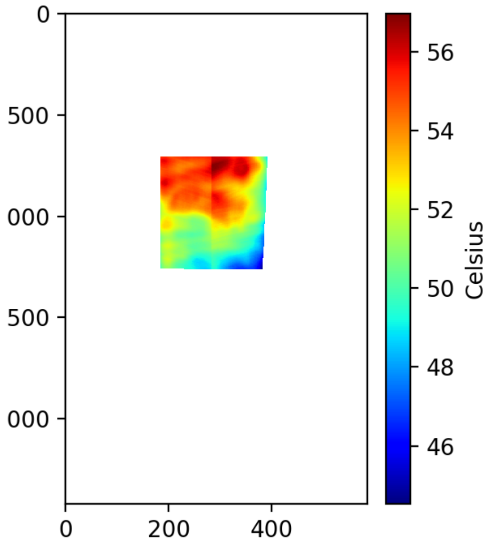


Effective temperature distribution

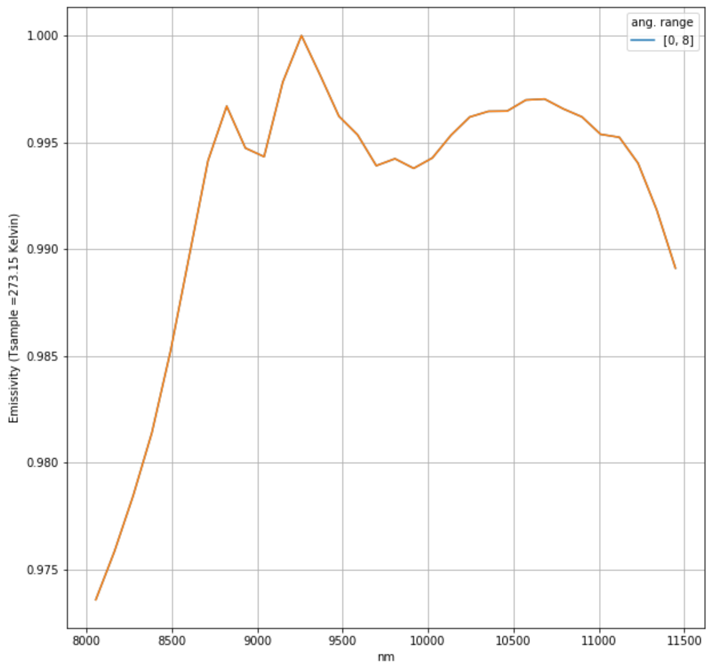


Relative emissivity

Shingles with red paint, synthetic enamel (PT02).

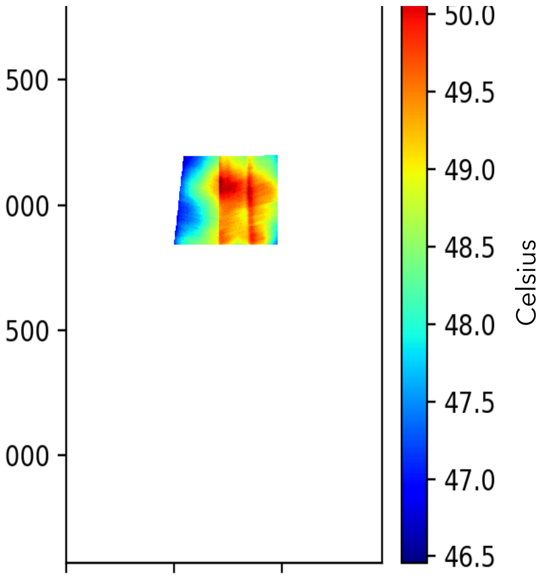


Effective temperature distribution

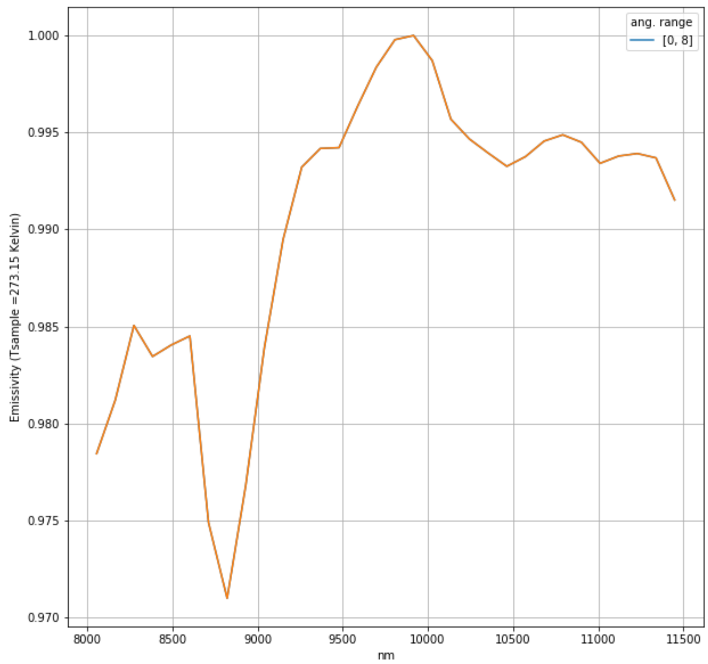


Relative emissivity

Plastic, methacrylate shingles, blue, shiny (P01).

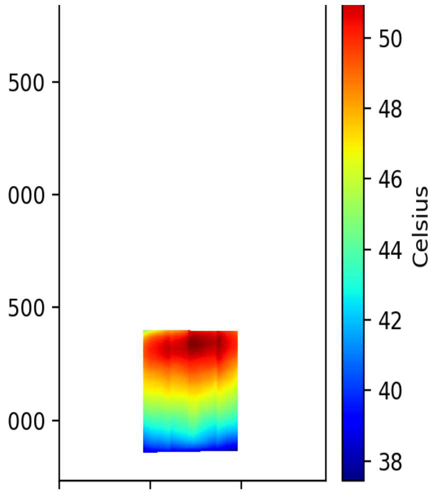


Effective temperature distribution

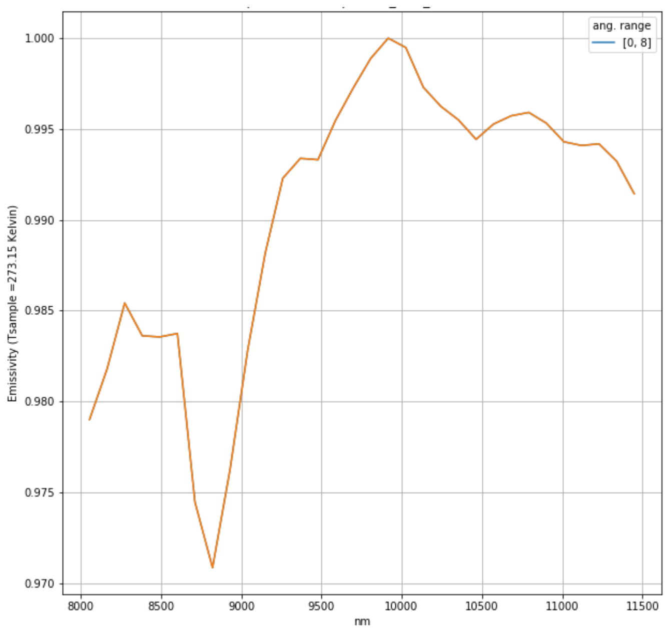


Relative emissivity

Plastic, methacrylate shingles, red, shiny (P02).

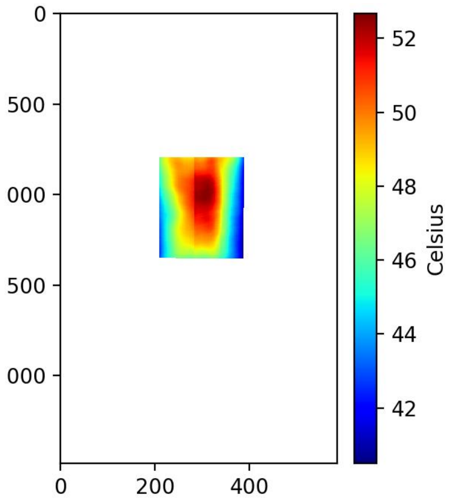


Effective temperature distribution

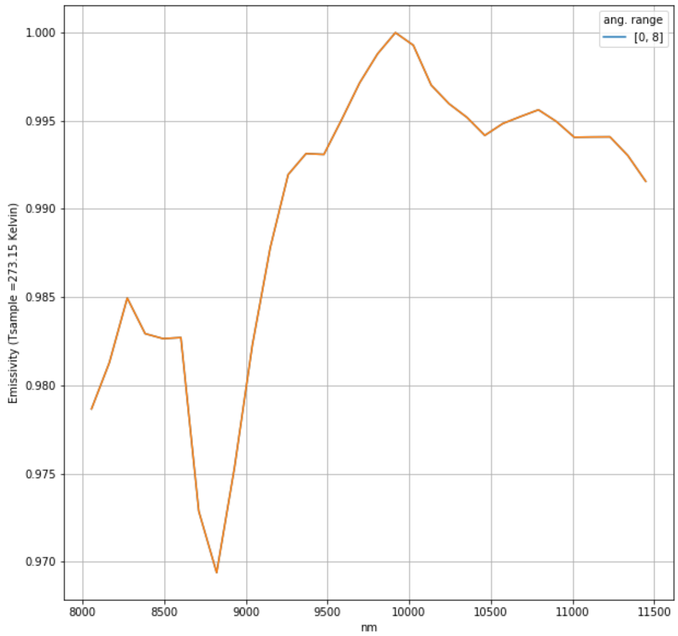


Relative emissivity

Plastic, methacrylate shingles, white, shiny (P03).

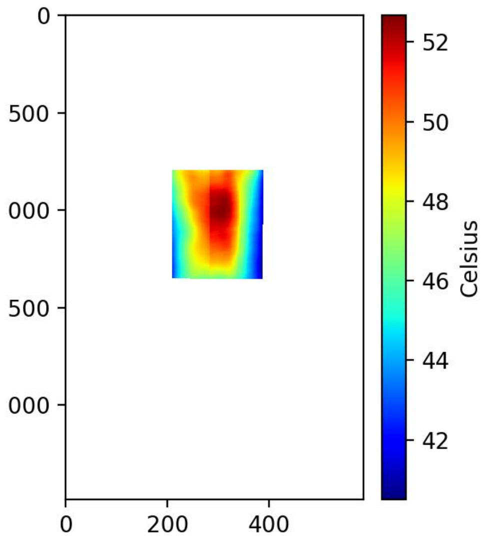


Effective temperature distribution

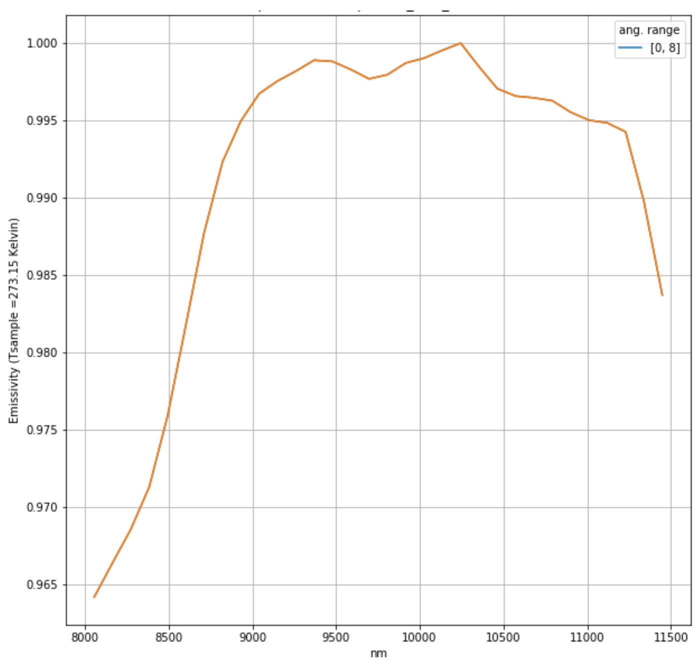


Relative emissivity

Plastic, polyvinyl chloride, white (P04).

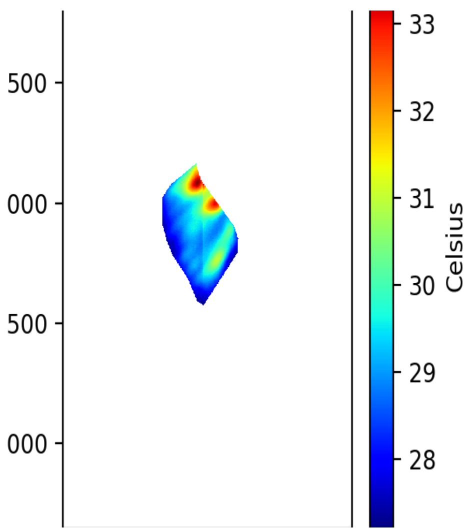


Effective temperature distribution

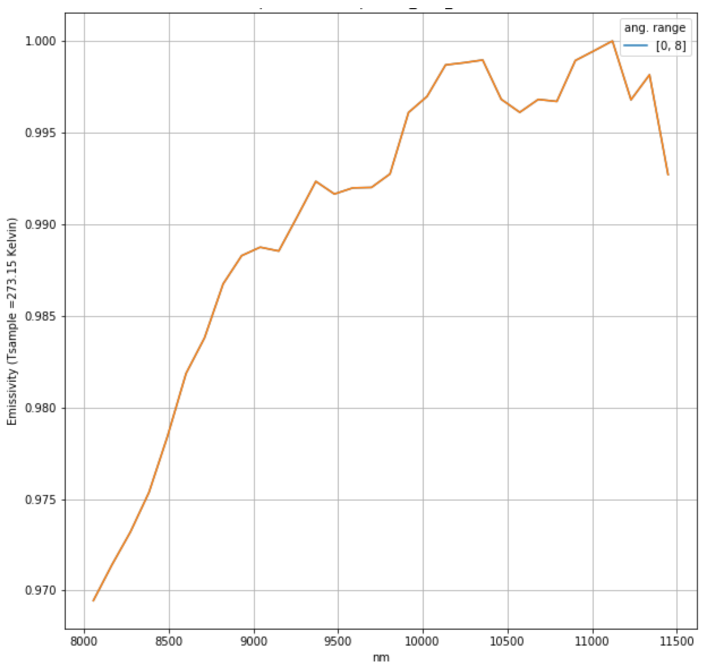


Relative emissivity

Plastic, polycarbonate shingles, white, shiny (P05).

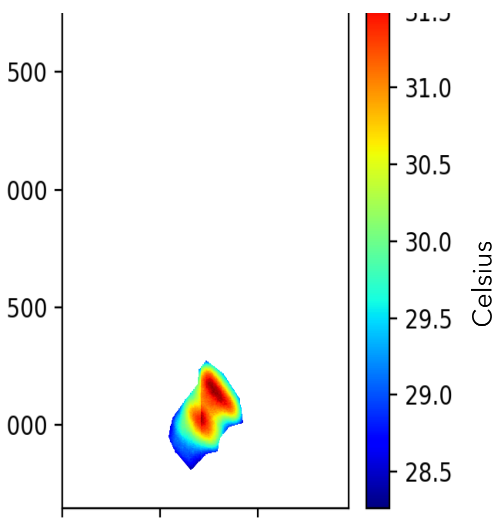


Effective temperature distribution

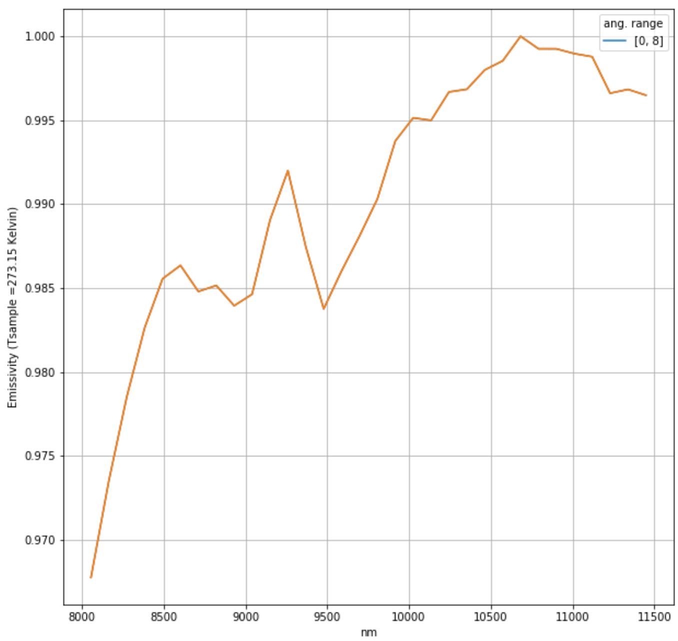


Relative emissivity

Plastic, polycarbonate shingles, translucent blue, shiny (P06).

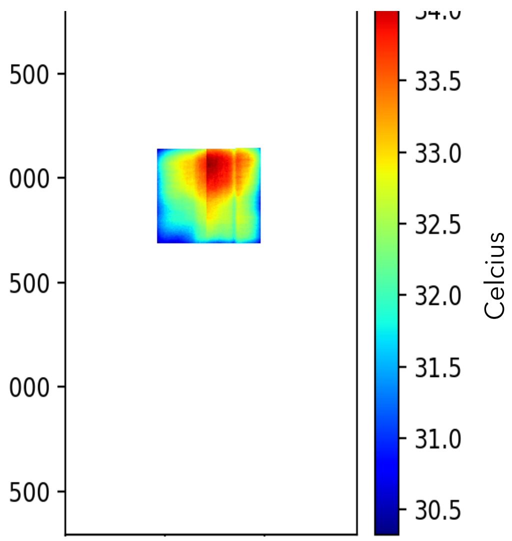


Effective temperature distribution

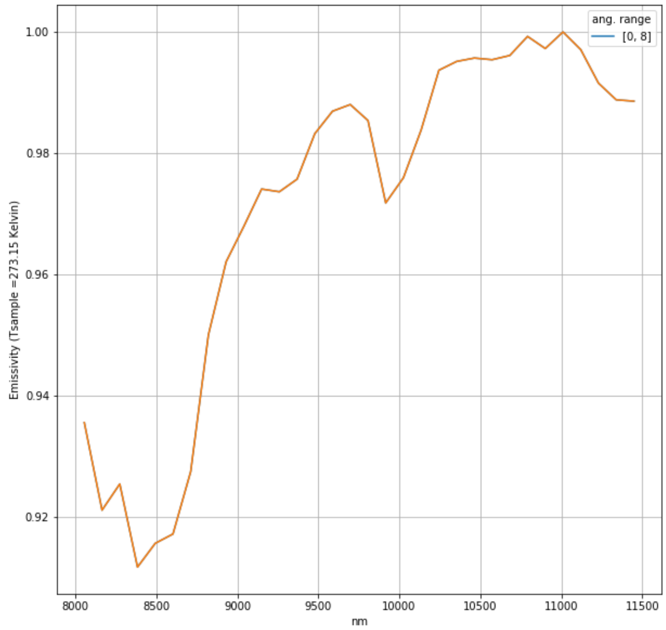


Relative emissivity

Plastic, polycarbonate shingles, translucent shiny (P07).

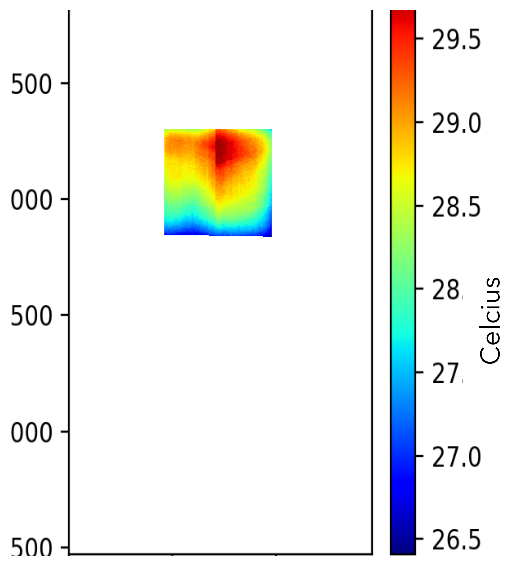


Effective temperature distribution

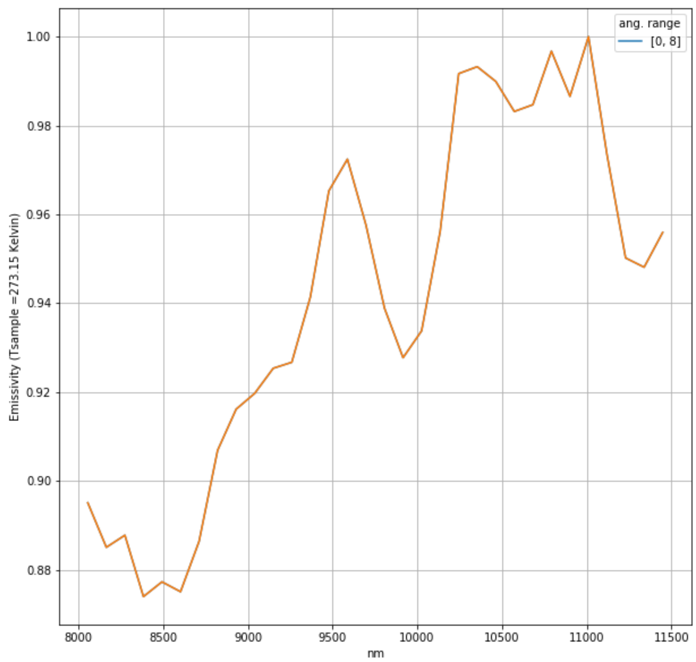


Relative emissivity

Plastic, polycarbonate shingles, translucent blue, shiny (P08).

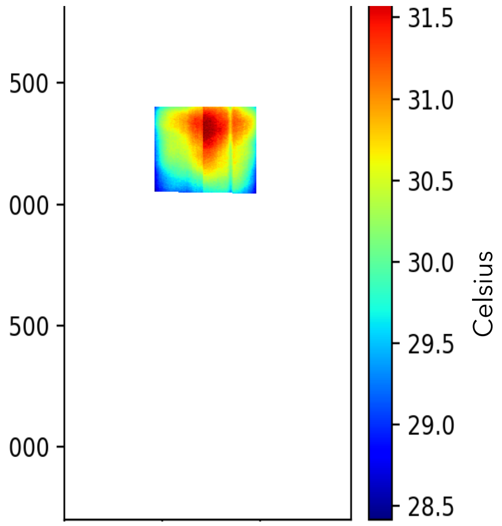


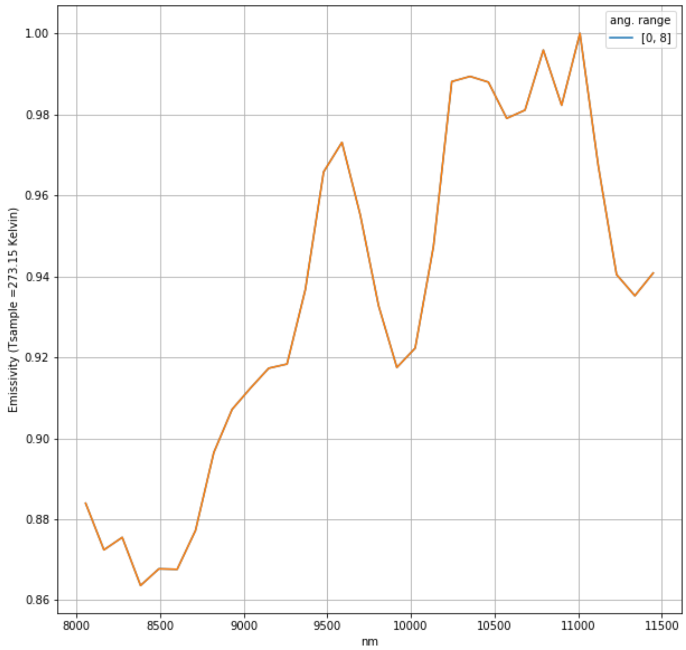
Effective temperature distribution



Relative emissivity

Plastic, polycarbonate shingles translucent red, shiny (P09).

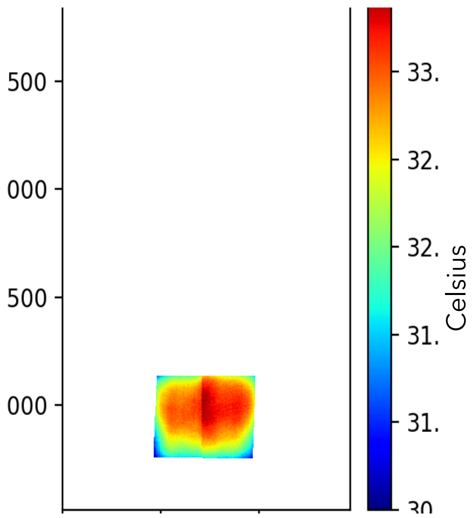


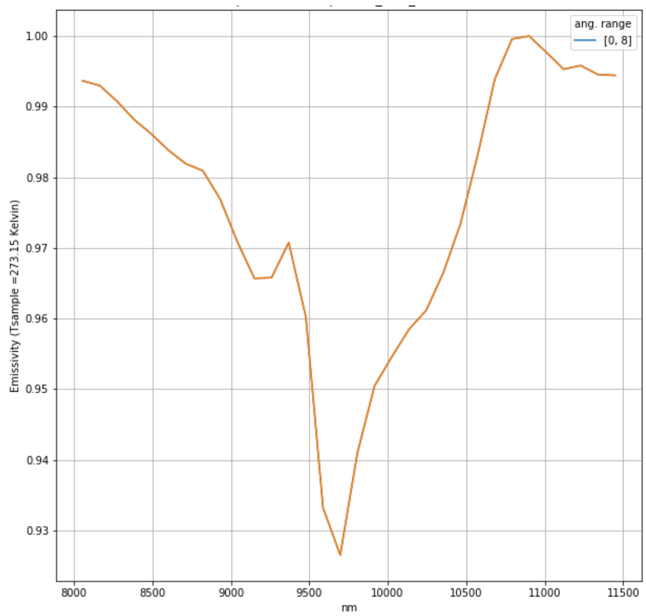


Effective temperature distribution

Relative emissivity

Plastic synthetic rubber ethylene-propylene, black, dull (P10).

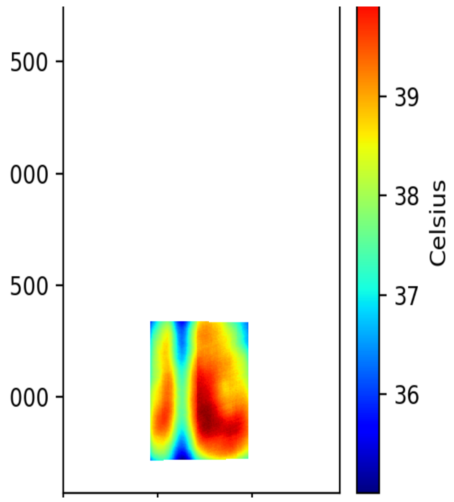


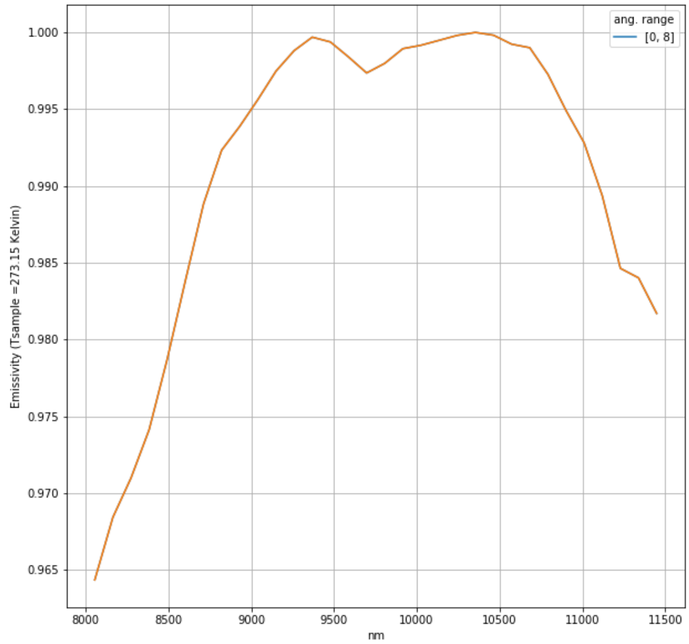


Effective temperature distribution

Relative emissivity

Plastic, asphalt polymer, black, dull (P11).

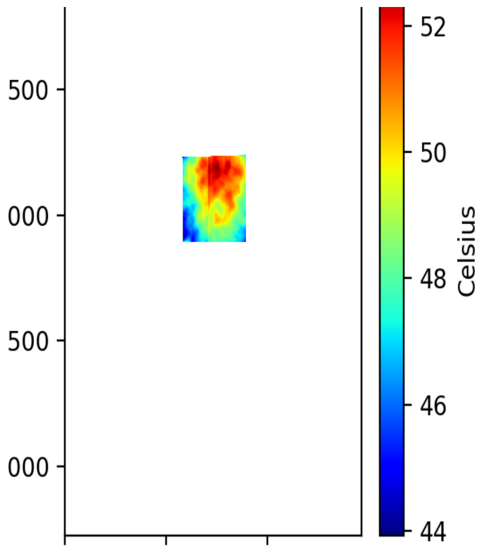


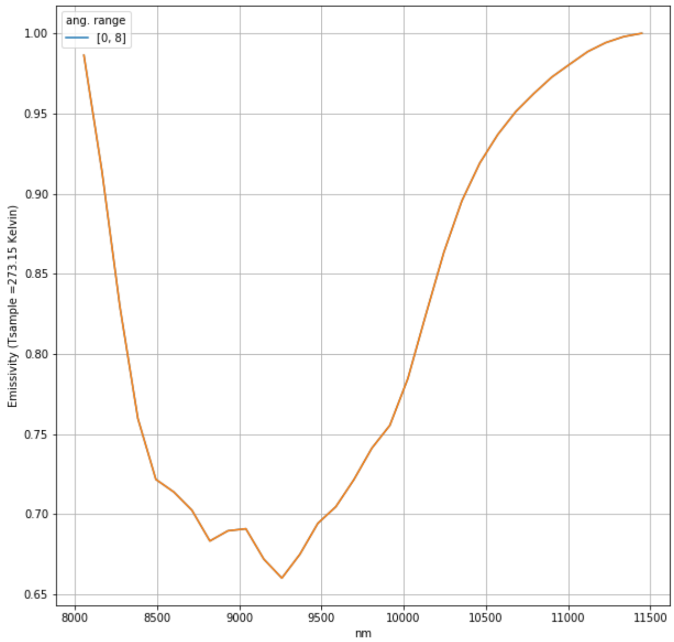


Effective temperature distribution

Relative emissivity

Stone, granite tiles multicoloured, white/black, dull (S01).

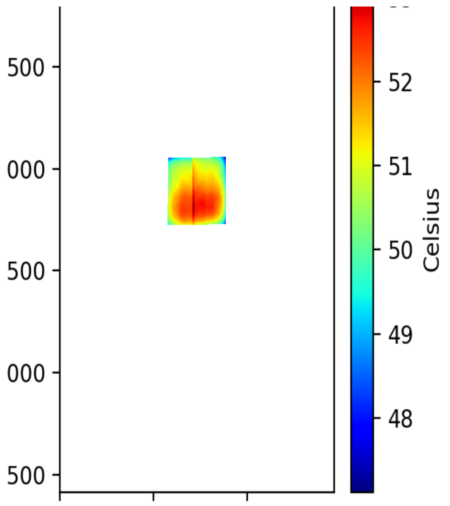




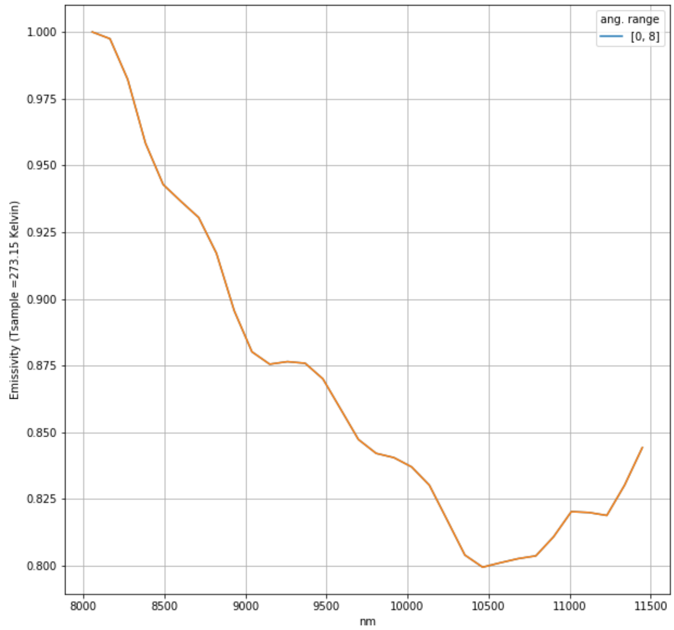
Effective temperature distribution

Relative emissivity

Stone, granite tiles multicoloured, black/grey/white, dull (S02).

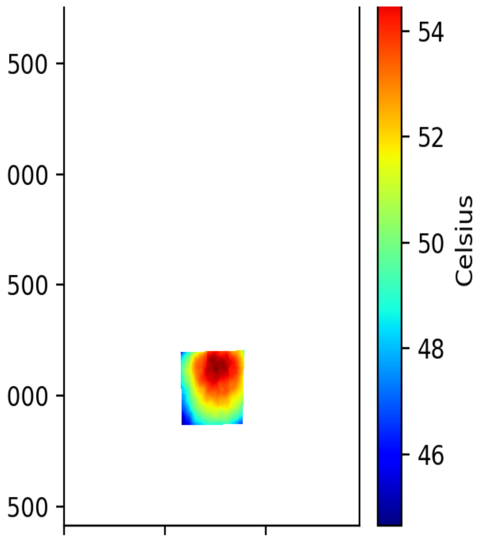


Effective temperature distribution

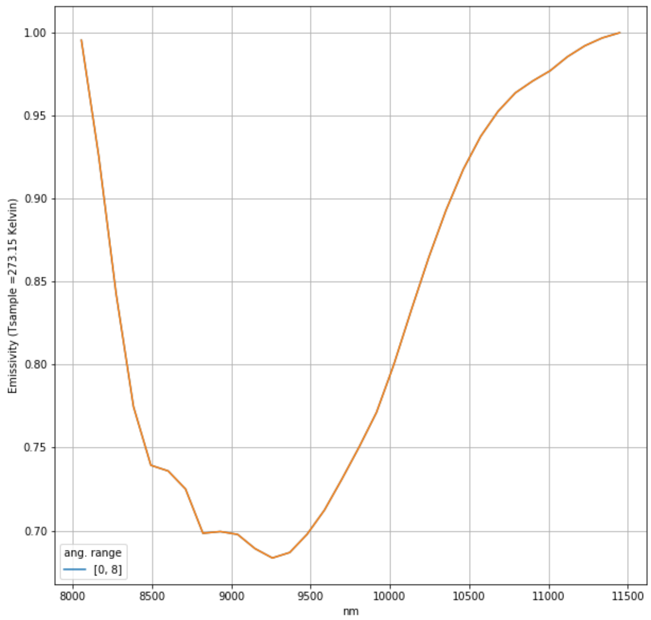


Relative emissivity

Stone, granite tiles multicoloured white/green, dull (S03).

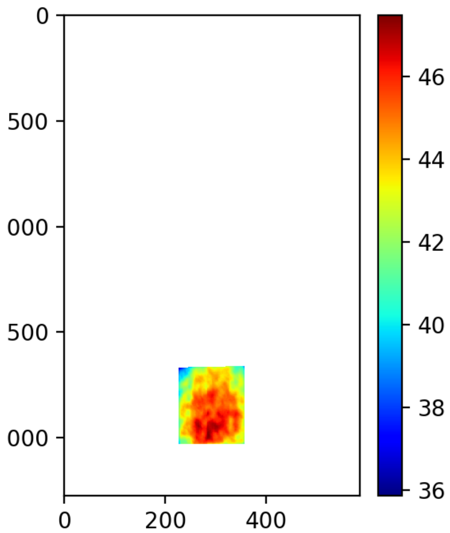


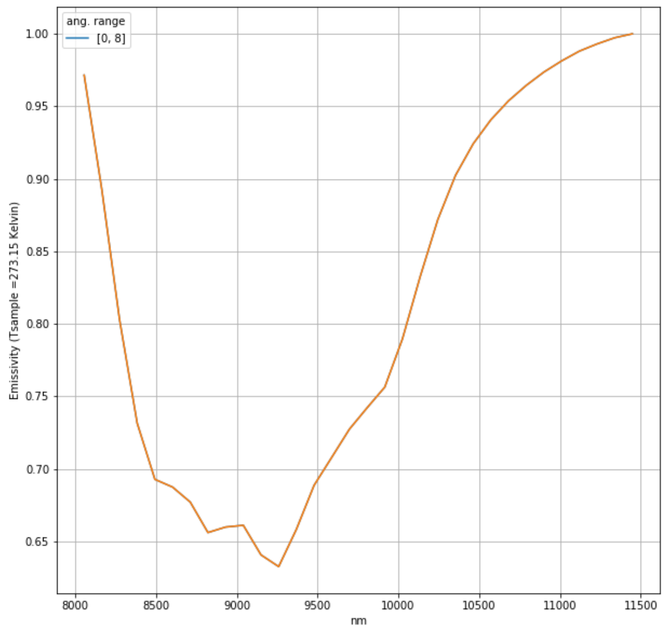
Effective temperature distribution



Relative emissivity

Stone, granite tiles multicoloured, white/pink/black, dull (S04).

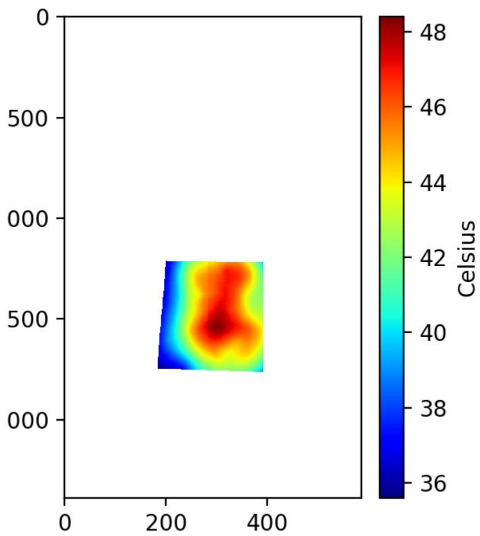


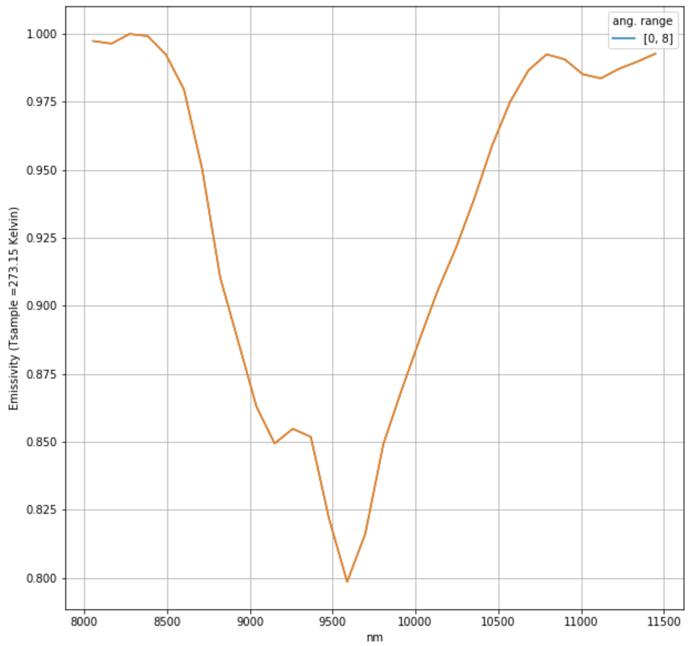


Effective temperature distribution

Relative emissivity

Stone, slate tiles, grey, dull (S05).

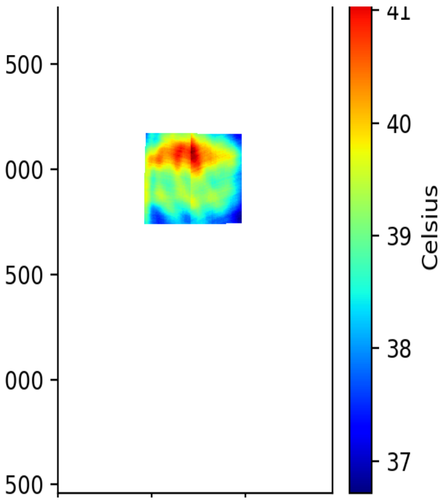




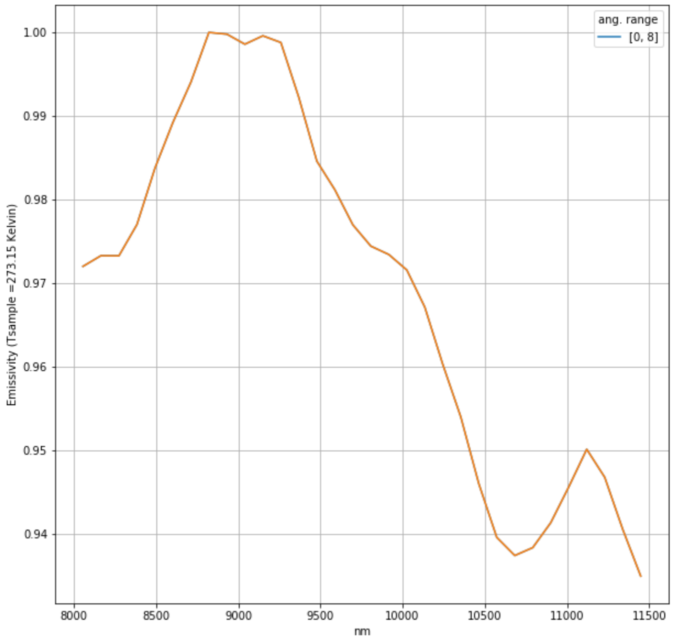
Effective temperature distribution

Relative emissivity

Wood, shingles dull, light brown, dull (W01).



Effective temperature distribution



Relative emissivity