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# Productivity of a building-integrated roof top greenhouse in a Mediterranean climate

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ABSTRACT

Urban Agriculture (UA) is an emerging field of agricultural production aimed to improve food security and the resilience of cities and to improve the environmental, social, and economic sustainability of urban areas. One of the options of UA are roof top greenhouses (RTGs), which are greenhouses built on the roof of a building, typically fitted with soilless culture systems. Further benefits can be achieved if the greenhouse and building are integrated, so that they exchange and optimise energy, water and $CO_2$ flows. Integration is possible if the RTG and the building can exchange air and can collect rain water or use properly treated grey water for irrigation. Such type of integrated RTG is referred to as i-RTG. Both the environmental profile and the social value of i-RTGs have been studied, but information on their productivity is rather scarce. As the economic viability of i-RTGs is given by the value of all services provided, including the yield, the productivity of such systems needs to be maximised. This study attempts this, through the analysis (and discussion) of an i-RTG built in a Mediterranean climate (Barcelona area, Spain), producing beef type tomatoes ("Coeur de boeuf" cultivar).

The experimental study showed that the i-RTG had poor light transmission. As a consequence, yield was low and the radiation use efficiency (RUE), referred to the outside radiation, was lower than in standard production (unheated greenhouses) in the same region. Nevertheless, RUE referred to the radiation above crop canopy, was similar in the i-RTG and standard greenhouses. Compared to conventional greenhouses in the area, which are generally unheated, a strong asset of the i-RTG was its improved (night-time) temperature regime, thanks to the thermal connection to the building. This advantage translates into energy savings referred to greenhouses on the ground, in case such greenhouses were heated.

In order to discuss possible improvements, we adapted an existing greenhouse tomato production model to simulate this particular type of system. After validation, we quantify and discuss the yield rise that could be achieved by improving transparency of the RTG and by increasing $CO_2$ concentration through daytime connection to the building. We show that there is potential to more than double the yield in comparison with the measured crop yield in the i-RTG. Last but not least, we discuss the option of switching to a cropping pattern more adequate for this growing system, that is: to extend the cropping cycle during the winter months, which is not possible in unheated greenhouses in the area.

To our knowledge, this work is the very first attempt to evaluate productivity of roof top greenhouses in mild winter regions and quantify options for improving their agronomic performance.

## 1. Introduction

Urban Agriculture (UA) is very fast developing as a response to increasing world urbanisation and welfare of urban populations, long supply chains and growing consumers' demand for fresh, high-quality food with little environmental footprint. There has been a recent

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increase of projects to promote the introduction of agricultural production in cities (Mok et al., 2013; Taylor and Taylor Lovell, 2012). Most of these projects are driven by social and environmental motives, but a growing number attempt commercial viability, aiming to cover a growing niche market, ready to pay premium price for short-supply-chain produce from urban farms or urban production sites inside the city.

There are many types of systems that are part of UA. They vary in status and ownership, and they meet different objectives. In terms of technology they rank from the very simple ones, such as community gardens for social inclusion or private gardens for self-supply, to very complex ones, such as indoor production with artificial lighting or climate-controlled plant factories. Today, UA is also implemented in buildings. Several authors define these forms of UA as vertical farming (VF) (Despommier, 2008; Germer et al., 2011) or as integrated farming in buildings (Caplow, 2009) or ZFarming (ZeroAcreageFarming) (Specht et al., 2014).

One fast-developing UA typology is that of roof top greenhouses (RTG)–a greenhouse built on the roof of a building–that typically generates produce via soilless culture systems (Cerón-Palma et al., 2012), in view of the static pressure that would be caused by soil growing. Commercial RTGs were recently erected in North America, such as (Gotham Greens, 2011) in Brooklyn, USA, with an area of 1400 $m^2$, or (Lufa Farms, 2013) with 2900 $m^2$ mostly devoted to produce traditional greenhouse crops (tomato, cucumber, pepper, etc.) for sale. Urban Farmers AG (UF) is a commercial company that initiated in May 2016 the operation of an aquaponics farm in The Hague (The Netherlands). It includes a 1200 $m^2$ RTG for the production of specialty vegetables (heirloom tomatoes, chilies, herbs, salads and micro-greens) and a recirculating aquaculture system (370 $m^2$) for the production of tilapia besides an indoor artificial lighting growth room of 200 $m^2$. The business model of most such facilities includes incomes from other services (f.i. social, research and/or exhibition) in addition to sale of produce.

Recently, (Sanyé-Mengual et al., 2015a) reviewed the benefits of RTGs, which were classified by their scale of application. For instance, global benefits (as the RTGs effect on climate change mitigation), local benefits (like naturalisation of urban areas), benefits for the greenhouse and building (viz. energy saving) and produce benefits (such as increasing freshness and food quality). Further benefits can be achieved if the greenhouse and building are integrated, so that they exchange and optimise energy flows, water flows and $CO_2$ flows. The integration is possible if the RTG and the building can exchange air and can collect rain water or properly treated grey water for irrigation. Such type of integrated RTG is named i-RTG. (Nadal et al., 2017).

Very few examples of greenhouses integrated with buildings are available. Close to the integrated RTG concept was the EU-financed Watergy project (http://www.watergy.de/) based on the construction of a facade greenhouse connected to a building. Watergy was mainly focused at reducing energy consumption in buildings and greenhouses in Northern Europe (Buchholz et al., 2006). The ongoing Spanish Fertilecity project (http://fertilecity.com/en/) has already produced valuable results in terms of environmental and economic assessments, stakeholders perception of UA and implementation potential of i-RTG in urban areas (Sanyé-Mengual et al., 2015 (a, b), 2016). One such facility is the ICTA-RTG built in 2014, which is a research-oriented i-RTG on top of a university building, the greenhouse where this research was carried on.

Our study is not focussed on the energy balance of the metabolism between building and i-RTG, as done by Nadal et al. (2017) who presented an energy and environmental assessment of the ICTA-RTG greenhouse. The study by Nadal et al. showed that the i-RTG recycles low-grade thermal energy from the building and uses it for growing vegetables. Besides, the i-RTG achieved annual saving of $CO_2$ (eq) emissions of 113.8 kg/$m^2$ year, relative to an equivalent, oil-heated greenhouse.

However, even when the focus of the i-RTG is on the value of additional services, it is important to maximise the agronomic value, in order to lower reliance on the value of those services. Nevertheless, an analysis of the greenhouse climate, crop response and potential increase in productivity based on climate management is still missing. It is also missing a discussion of the i-RTG performance in comparison with conventional greenhouses in the areas where the winter climate is mild and where the vast majority of greenhouses are passive or unheated. This article is aimed to cover such lack of information. Most specifically its objectives are:

- To evaluate productivity of an integrated RTG (i-RTG) in a Mediterranean climate, and relate it to the properties of the greenhouse and building
- To propose (and assess the value of) means to increase the yield of such systems, viz. the enhancement of greenhouse light transmission, the use of $CO_2$ enrichment and the extension of the growing period during the winter months.

## 2. Materials and methods

The research was conducted on a roof top greenhouse (i-RTG) erected in 2014 on top of the building that hosts the Institute of Environmental Science and Technology (ICTA Universitat Autonoma of Barcelona, Spain). The building is used for research and teaching purposes; it has no particular equipment or machinery which can generate large amount of waste heat, apart from the laboratory equipment (mostly for chemical analysis) and the active heating and cooling of the workspaces and laboratories, which is a ground-source heat pump. The building has an area of 7500 $m^2$ and has a square roof of 36 m by 36 m. It is a six-storey building (two underground floors and 4 above ground floors), around a central atrium. A fifth aboveground level, meant for greenhouse cultivation in four compartments (measuring 128 $m^2$ each) is covered with a polycarbonate roof throughout, including the atrium. The inner side-wall of each compartment is a polyethylene-film curtain that could be rolled up or down to connect or isolate the greenhouse with the building's atrium. At the time of the work described here only one compartment was cultivated.

The greenhouse structure is a two-span metal-frame covered with single-sheet corrugated polycarbonate panels. It is 19.55 m long and 6.55 m wide (Fig. 1). The gutter height is 4 m. The roof slope is 45°, designed to allow condensation easily running down the polycarbonate panels. The greenhouse has continuous double roof ventilation on each span (which makes a total of four roof ventilators 19.55 m long) as well as four flap ventilators on the exterior side wall (the one on the street side). Ventilation was controlled by a Siemens control software. The Siemens software offers independent controls of the ICTA building and the i-RTG thermal condition. The opening angle of side and roof ventilators varied according to the i-RTG air temperature (Nadal et al., 2017). The i-RTG floor is a 6-cm thick concrete slab thermally insulated underneath from the lower floor.

The i-RTG had no active heating. It benefited from the building's thermal stability as well as the air exchange between the greenhouse and the building, which was possible through the atrium and the cavity of the double skin façade. Such air exchange was an indirect air exchange from the building since, at night, the sidewall curtains that connected the i-RTG with the atrium and the double skin cavity were rolled up. There was no active exchange of air (no fans forcing mechanically the air exchange). At the moment, the integration of the i-RTG and the building is unidirectional (from building to greenhouse), though actions are under way to make it bidirectional by discharging warm i-RTG air into the building via service ducts.

Rain water was harvested from the roof of the ICTA building as well as the nearest building. After passing through a primary filter to remove solids, rain water was collected in a 100 $m^3$ underground tank and stored for irrigation. Tap water could also be used for irrigation