International Conference on Smart Infrastructure and Construction 2019 (ICSIC):
Driving data-informed decision-making

DeJong, Schooling and Viggiani
ISBN 978-0-7277-6466-9
https://doi.org/10.1680/icsic.64669.133

MONITORING THE PERFORMANCE OF AN UNDERGROUND HYDROPONIC FARM

M. Jans-Singh[1], P. Fidler[1], R.M. Ward[1,2] and R. Choudhary[1,2]*

[1]*Department of Engineering, University of Cambridge, Cambridge CB2 1PZ, UK*
[2]*Alan Turing Institute, British Library, London NW1 2DB, UK*
* *Corresponding author*

ABSTRACT As urban populations are set to rise by 2.6 billion by 2050, placing greater strain on the availability of natural resources in cities, there is growing interest in hydroponics as a resource and space efficient method to grow food closer to point of use. While controlled environment agriculture (CEA) is increasingly being used in greenhouses, one cannot rely on models alone to create optimal environments with minimal resource use. Growing Underground is a unique case in London, where WW2 air raid shelters, derelict since the 1960s, have been transformed to house a hydroponic farm. This paper presents the case study of monitoring this start-up hydroponic farm to improve crop growth and minimise energy use. It shows the development of monitoring techniques through a wireless sensor network and the manually recording of data. A set of indicative parameters is derived from the monitored variables in this three-year long study to analyse dependencies and correlations. The data are organised into environmental parameters (temperature, relative humidity, change in CO2), control parameters (energy use, water use, ventilation, lights), and crop growth parameters (crop health, yield and number of growing days). The relationships found between the variables are then used to understand how to improve the performance of the farm, namely, to adapt farm configurations, derive the optimal growing conditions, and improve the resource use efficiency.

1. Introduction

By 2050 the world's population is expected to increase by 3.5 billion, most of whom will live in cities, placing greater stress on infrastructure, resources and food security (Garnett, 2013). Urban agriculture is being increasingly investigated as an alternative local source of food, notably using hydroponics. Integrating urban farms within dense environments has the potential to utilise waste infrastructure and resources within cities and at the same time provide jobs and improve food security (Pons *et al.*, 2015; Benis, Reinhart and Ferrao, 2017). This paper presents the unique case study of monitoring the development of a start-up hydroponic farm in derelict London tunnels, Growing Underground.

Defined sometimes as plant factories, integrated greenhouses, or vertical farming, hydroponic farms are becoming increasingly considered in our cities by councils, non-profits and commercial enterprises. Their potential in terms of Life Cycle Assessment has been examined by many researchers (Despommier, 2011; Specht *et al.*, 2013). However, there is a lack of understanding of how well these systems can be integrated into existing infrastructure, and how their environment can be optimized in an efficient manner. Scientific models for plant growth are largely empirical and developed for certain types of commercial plants (Körner *et al.*, 2007; van Straten and Henten, 2010), hence it is not possible to rely on models alone. This work presents a unique case study of monitoring both qualitative and quantitative data in an existing hydroponic farm in London. We describe the monitoring design and demonstrate how this data is used by the urban farm for two purposes: (a) to optimize their environment on a day to day basis, and (b) to design the future extensions of the urban farm.

This paper begins by describing the monitoring network in Growing Underground, as well as the challenges faced to design such a network in this environment. The data is then cross-analysed with each other by finding interpretative parameters to establish dependencies, and sub-dividing the dataset into interesting groups (based on seasonality, crop performance, optimal conditions). This leads to the final section, which presents examples of how the data is used to derive key performance indicators and track these indicators under changing conditions, in future designs of the farm.

Figure 1 View of Growing Underground farm from the back of the tunnel

1.1 Background on Growing Underground

Growing Underground is an unheated hydroponic farm, installed in tunnels designed as a WW2 air raid shelter in the 1940s, 33m below ground (Zero Carbon Foods Ltd, 2017). Founders Richard Ballard and Steven Dring wished to integrate hydroponics into derelict space in London, to grow microgreens closer to their point of use, which spurred the development of the farm in these tunnels abandoned since they last housed the Windrush generation of migrants in the 60s. The farm initially catered to hotels and restaurants and has expanded to become a supplier of M&S and Ocado. The main crops are peashoots, a variety of basil, coriander, parsley, salad rocket, pink radish and mustard plants. The farm consists of two parallel tunnels, running on two levels and spanning approximately 400 m. Currently only half the upper tunnel is used for farming, with a growing space of around 560 m^2, and is projected for major extensions in the near future.

Traditionally, hydroponic farms are glass greenhouses with controlled environments and high energy use intensity, thus this farm is a unique environment. Literature surrounding optimal growing conditions in greenhouses focus on maintaining temperature, relative humidity, air velocity and CO_2 (to some extent) within ideal bounds. Managing these fine bounds within a long tunnel environment, while optimising the use of energy, is a difficult task for the farm operators on a day to day basis. Designed in the 1940s, the ventilation system of these ex-shelters has to rival with the expectations of Controlled Environment Agriculture (CEA), but careful studying of the environmental conditions can help optimise the farm configuration and highlight the important factors to consider.

The main objectives of monitoring can be defined by these two points:

1. Keep growing: maintain adequate conditions for optimal crop growth at all times
2. Optimise energy use: minimise the resources put into the farm (water, fans, lighting) while optimising conditions for crop growth and maintain structural integrity.

As sensor networks become increasingly used in horticulture, it is important to transform the data collected into information to lead to better practice, especially in bespoke sites such as Growing Underground (GU). The challenges in data-driven models do not lie in data analysis alone. Sensors are known for their limitations which include low battery power, limited computational capability and small memory (Aqeel-ur-Rehman *et al.*, 2014). Consequently, a range of methods were deployed to collect data in GU: from the design of a sensor network which sends data in real time to a viewing platform, and to manual reporting of control conditions within the farm.

2. Monitoring in Growing Underground

2.1 Continuously logged data

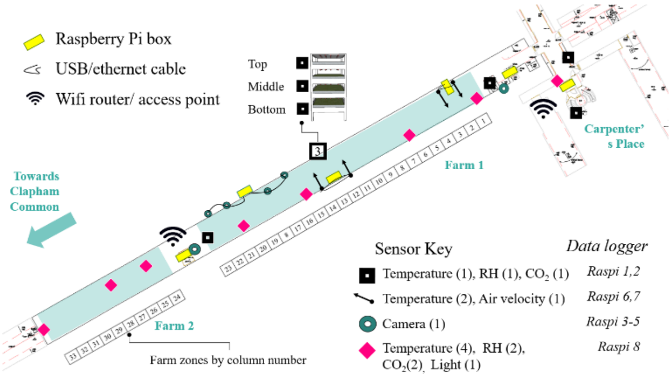
Five environmental variables are continuously monitored in Growing Underground: temperature, relative humidity, CO_2 concentration, air velocity and light levels. For each sensor, the time since installation, location, and measurement interval are listed in Table 1, and are mapped in Figure 2. The location of the sensors linked to the Wireless Sensor Network (WSN) is illustrated in Figure 2a, while those which require manual downloading are in Figure 2b.

Table 1 Continuous data logging for GU

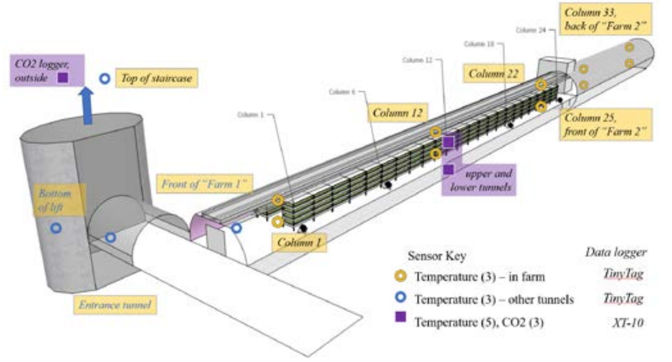
	Time interval	Description	Data logger	Recorded since
Temperature				
(1)	4 min	5 sensors in farm, and 2 sensors in entrance tunnels	Raspi 1, 2	March 2015
(2)	4 min	4 sensors in Farm 1 integrated to air velocity sensor (1)	Raspi 6,7	November 2017
(3)	15 min	4 sensors distributed in the entrance tunnels, and 10 along the farms	TinyTag	February 2018
(4)	8 min	7 sensors distributed in farm and on shelves	Raspi 8	December 2018
(5)	10 min	3 sensors in CO2 monitors: outside, upper and lower tunnels	XT-10	August 2018
Relative Humidity (RH)				
(1)	4 min	5 sensors in farm, and 2 sensors in entrance tunnels	Raspi 1, 2	March 2015
(2)	8 min	7 sensors distributed in farm and on shelves	Raspi 8	December 2018
Carbon dioxide				
(1)	4 min	5 sensors in farm, and 2 sensors in entrance tunnels	Raspi 1, 2	March 2015
(2)	8 min	6 sensors distributed in farm and on shelves	Raspi 8	December 2018
(3)	10 min	3 sensors from manually calibrated loggers	XT-10	August 2018
Air velocity				
(1)	4 minutes	4 anemometers, two at the front, and two in the middle of Farm 1	Raspi 6,7	November 2017
Light				
(1a)	8 min	7 photodiodes distributed in the farm	Raspi 8	December 2018
(1b)	8 min	7 lux metres distributed in the farm	Raspi 8	December 2018
Outdoor weather				
(1)	1 hour	Temperature, relative humidity and rainfall from the Met Office St James' Park weather station		January 2016
(2)	1 hour	Temperature, relative humidity and rainfall from Open Weather Maps at Clapham		November 2017
Energy use				
(1)	30 min	Meter reading at Carpenter's Place (CP)		March 2018
(2)	30 min	Meter reading at Clapham Common (CC)		

The WSN consists of the sensors transmitting data to Raspberry Pi loggers that are configured to process the data and send it to servers directly managed by the research team in a convenient format, and also store the data on SD cards when the wireless service goes down. A web platform was built to visualise in real-time the data acquisition. When Growing Underground engaged the services of Datch Systems Limited to provide enhanced data visualisation capabilities, it was relatively easy to add scripts to send our data to Datch Systems' servers as well.

Figure 2
(2a) Map of the wireless sensor network in the farm tunnels. Refer to Table 1 for description of the sensor linked to the monitored variable.



(2b) Map of loggers from which data must be downloaded manually



Temperature (1), relative humidity (1) and CO2 (1) are captured using AdvanticSys IAQM-THCO2 sensors. These are mains powered and connect to each other (via Wireless Modbus bridges) and to two Modbus/RTU dataloggers via a wireless mesh network using IEEE 802.15.4 radios (Advanticsys, 2017). These loggers originally sent data to a dashboard accessible on the subscription AdvanticSys website but were reconfigured to allow greater data accessibility. The original dataloggers were replaced by two Raspberry Pi single-board computers running Linux and fitted with USB-to-RS-485 adapters (Raspi 1 and 2 in Table 1), linked to the ADSL router directly with an Ethernet cable.

Temperature (2) and air velocity (1) are measured with four E+E Elektronik EE671 anemometers, added in November 2017. Available with either analogue or Modbus RTU outputs, the latter was chosen to connect the sensors to two additional Raspberry Pi computers using an RS-485 adapter. Each Raspberry Pi data logger is connected to two air velocity sensors (Figure 2a). Data is sent from Raspi 6 and 7 over WiFi to the local router. Additional WiFi access points were installed in the tunnel to allow greater flexibility in sensors placement.

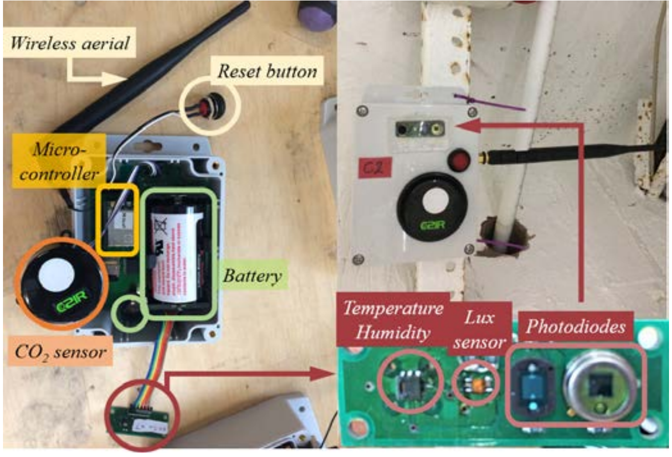
Temperature (3) corresponds to the measurements from the TinyTag data loggers (Gemini Data Loggers, 2018), pictured in Figure 3 and locations shown in Figure 2(b). These versatile sensors are battery powered and waterproof, but the data needs to be manually downloaded off each sensor every three months using an inductive pad. This allows the sensors to be placed in areas not covered by a wireless network, such as outside, in empty tunnels and at several points along the farm which do not have electrical sockets. They provide information about the spatial variations of temperature along the tunnels.

Camera sensors: One goal of the project was to monitor plant growth. It was therefore decided to use simple USB webcams connected to several Raspberry Pi computers (Raspi 3-8), with four cameras per Pi (Figure 3). These were configured to take a photo every 15 minutes. It was hoped that these images could be analysed to provide an indication of the rate of leaf growth. These sensors were not a success. As production in the farm moves from rack to rack, the cameras needed to be repositioned to point at a new batch of product. The team were never able to get the necessary 'buy-in' from the farm staff, possibly due to concerns over privacy. No useful data was collected from the cameras and their use is not considered further in this paper.

Figure 3 Picture of a camera and TinyTag (Temperature (3)) sensors in the tunnel

Temperature (4), RH (2), CO₂ (2) and light (1a and 1b) are monitored with the new battery-powered wireless sensors designed by the team (Figure 4). The sensors create a low-power wireless mesh network with each other so that data can be sent even when out of range from the WiFi network, and are fitted with an SD card in case the mesh fails. The sensors used were a COZIR Non-Dispersive Infrared (NDIR) CO2 sensor from Gas Sensing Limited, a SHT21 temperature and humidity sensor from Sensirion (an I^{2}C version of the SHT7x sensor used in the AdvanticSys sensors) and three different light sensors to measure the photosynthetically active radiation (PAR) in the tunnel: a digital OPT3001 and two analogue photodiodes. The sensors were connected to a deRFmega128 wireless microcontroller from Dresden Elektronik – based around the Atmel Atmega128RFA1 chip. The firmware for the new device was based on Contiki OS (Dunkels et al. 2004) using the 6LoWPAN/IPv6 radio stack. The datalogger consists of a Raspberry Pi connected to a deRFmega128 module with no sensors. It connects to the Internet via a WiFi connection to the ADSL router.

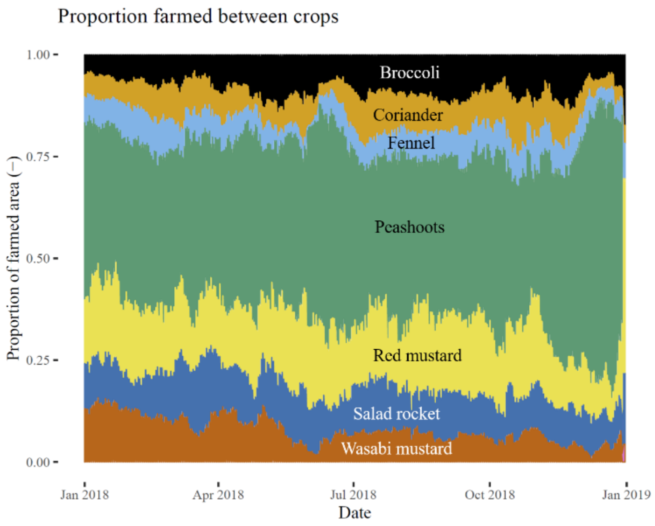
Figure 4 Pictures of the development of the Light, CO_2 temperature and RH sensor



2.4 Manually recorded data

It was not possible to automatically log crop data and individual actions on the farm. We have therefore assembled a set of data that is manually recorded (described in Table 2). For instance, the specific location, type and growth period of every single crop is recorded into an online spreadsheet by the farm workers. This data gives information about what type of crop was being grown in the farm over time, as illustrated in Figure 5.

Figure 5 Proportion of crops grown the farm in 2018



Qualitative comments about the farm's environmental conditions are inferred from a text-based keyword analysis to mark periods of operational change. Trigger dates to look at contain comments such as: "dry/wet" crops, movement of equipment, doors were opened or closed, "lots of condensation" (example of comments in Figure 6).

Figure 6 Example of pertinent recorded farm comments, from Spring 2018

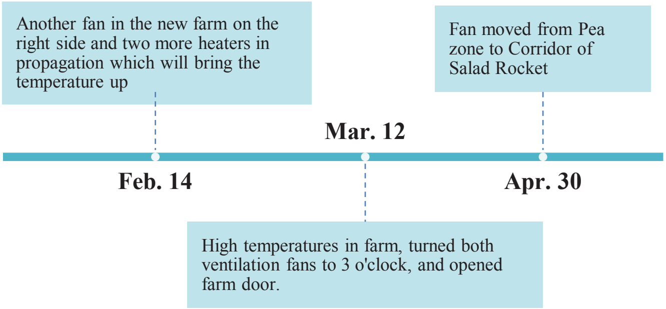


Table 2 Summary of manually recorded data

Name	Description	Measurement rate	Unit
Type of crop	e.g. broccoli, peashoots, celery	Daily since February 2016	Name
Mass harvested	Mass of crops harvested	Daily since February 2016	g
Growing days	Number of days propagating, underlights and total till harvest	Daily since November 2017	Number
Location of each crop	According to column, aisle, shelf	Daily since January 2017	(x,y,z)
Amount wasted	Surplus or diseased quantity on harvest batch	When applicable since January 2018	%
Area grown	Area of bench occupied by crop	Daily since January 2016	m^2
Water use	Water level in tanks	Weekly/monthly since August 2018	L
Comments	Major changes to farm configuration,	When applicable	
Ventilation setting	Dial turned on the extraction fan	When changed since January 2017	Visual
Status of doors	Doors affecting the ventilation area	When changed since November 2017	Open/ Closed/ Ajar
Air velocity	Point measurements with hand-held thermal anemometer	On occasion	m/s

2.5 Challenges with data collection

Gathering data in an operating hydroponic farm presents challenges of metering in a high humidity environment with continuous operations in the farm (Teitel, Atias and Barak, 2010; Chaudhary, Nayse and Waghmare, 2011; Park and Park, 2011). In addition, an underground environment poses extra challenges of network connectivity and limited locations where sensors can be feasibly installed. As a result, a range of different sensors and recording methods were trialled over three years. For instance, energy readings were recorded manually for two years on week days until an automatic meter was installed. Regarding air velocity, several field visits taking point measurements with a thermal anemometer were necessary to identify the most representative locations to install the air velocity sensors. Some sensors could not connect to the wireless network, manual data was not recorded at weekends or during holidays, and there were periods when sensors were displaced or ran out of battery power. A major limitation to sensing was also the limited points of access to mains electrical power in the tunnels.

It is also important to use several different sensors, each monitoring the same parameter, to cross-calibrate the data. For instance, CO_2 concentration is measured through NDIR (non-dispersive infrared) which has a tendency to drift over time, and sensors typically auto-calibrate against the daily minimum, which is set to be atmospheric (400 ppm). As this is not the case on our site, the sensors require regular manual calibration with outside air, otherwise they can only be used to analyse the relative change in CO_2 levels, but not the absolute value.

2.6 Parameters derived from the data

To derive meaning from the measured data, the measurements were combined into a set of parameters which are described in Table 3. When daily data were not available (such as water tank levels, mass harvested or energy use), they were disaggregated to a daily level proportionally. Furthermore, temperature, air velocity, RH and crop growth data were available for different locations along the tunnel, which enabled interpretation of the environment at different locations within the tunnels and as well as across time.

Table 3 Derived parameters from gathered data. The timestep column indicates the resolution (hourly, daily, bi-daily, monthly)

Derived parameter (unit)	Timestep	Calculation methodology
Temperature in the tunnel (°C)	Hourly Daily: night 1am and day 1pm	Taken as the weighted average by location of the temperature sensors in the farm
Relative humidity – Acceptable conditions [0 – 1]	Hourly	Taken as proportion to acceptable level [45%-65%]
Air mixing (horizontal and vertical)	Hourly	From horizontal and vertical stratification of temperature
Air velocity	Hourly	Average (including calibration correction for low air velocities), looked at in combination with door status (open/ closed) and ventilation setting
Air change rate (h^{-1})	Daily	Difference between the max and min CO2 level in the day
Length of photo-period (-)	Daily	Derived from energy use (time of energy use change – only since hourly metering, period was constant at 18hours)
Outdoor temperature (°C), relative humidity (%)	Hourly and Night/Day differentiation	Measured hourly, and average night-time/daytime (corresponding to photoperiod)
Precipitation (mm) & relative humidity (%)	Hourly (+1, +2, +3 hours, +12 hours, + 1 day) and Daily	Correlation window is analysed with delay
Percentage of occupied area of farm (%)	Daily	Disaggregation of harvest data in between date underlights and harvested, taken as proportion of farm with increasing farmed area.
Yield performance of three main and sufficiently representative crops: peashoots, wasabi mustard and salad rocket (-)	Daily	Taken as the eventual yield performance of each crop, for a given day. Yield is calculated by (mass harvested + surplus)/area [g/m^2]. Yield performance is taken against the average yield of that crop.
Growing days of crop (-)	Daily	Taken as eventual (number of growing days)/(average number of growing days for crop)
Energy use (kWh)	Daily, Monthly	Sum of metred energy use, as fraction of capacity
Water use (L)	Daily, Monthly	Disaggregated water quantity filled in water tanks by calendar day
Crops (g/m^2)	Daily, Monthly	Quantity grown per calendar month
Crop health (%)	Daily	Percentage lost to crop disease

3. Examples of optimising the farm with monitoring data

3.1 Determining optimal conditions for growth

The threshold values of optimal environmental conditions for the microgreens grown in the tunnel were first identified through a literature review, and then adapted through observation of the crop health over the three years of monitoring. These are summarised in Table 4. For example, relative humidity needs to be lower than conventional greenhouses due to condensation and the high risk of mould given the limited airflow in the tunnel. Temperature patterns depend on LED lights, which also serve as the main heating source in the tunnels. The monitoring data can thus be used to ensure these five environmental variables stay within the bounds indicated in Table 4.

Table 4 Optimal environmental conditions for crop growth in Growing Underground

Environmental factor	For lettuce, from literature	Adapted values for Growing Underground
Temperature	Between 20 and 25°C, optimal water and air at 24 °C (Thompson and Langhans, 1998)	Night time: 17-22°C Daytime: 21-26°C
Relative Humidity	Between 60 and 80%	Between 45 and 65%
CO_2 concentration	Keep above 400ppm, optimal at 1000ppm, carbon enrichment only with less than 3.5 ACH	Keep air change per hour as low as possible (measure is ventilation setting)
Air current speed	Significant yield improvements from 0.01 to 0.2 m/s, No significant change past 0.5 m/s	By location: 1 m/s through the corridor yields 0.1-0.3 m/s over the crops on most shelves
Light	High LUE at early growth stages Photoperiod of 18 hours optimal (Tei, Scaife and Aikman, 1996)	Data not available yet, currently 18 hours.

3.2 Identifying spatial variation in crop growth

We found that crop growth could be characterised by three variables that are not necessarily correlated: (1) number of growing days to reach desired size, (2) yield per area (for given number of seeds), and (3) crop health (percentage of crops diseased).

Crop yield data was divided into longitudinal zones along the tunnels (referred to as columns) in order to better understand how the spatial variations of environmental conditions affect crop growth. The data showed that, on an average, the crop yield was best in the middle of the farm (columns 9-20). The lower plot in Figure 7 shows for example that wasabi mustard tended to grow less well towards the end of the tunnels, in columns 30-31. The lower yields on the edges of the farm are attributed to the lower temperatures (Figure 9) and lower air velocities (Figure 12). Crops also tended to grow less well on the bottom shelf (colder temperatures), but there was no significant difference between the left and right aisles, suggesting sufficiently symmetrical conditions.

Figure 7 Yield performance of main crops grown by location along the tunnel, for year 2017 (top) and 2018 (bottom)

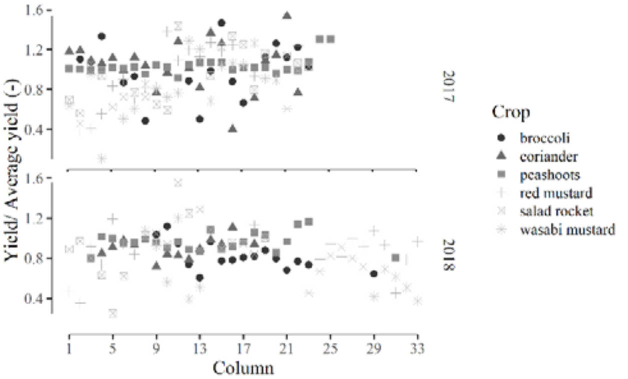


Figure 8 Proportion of the total harvested area in the year, by crop, at each column along the farm

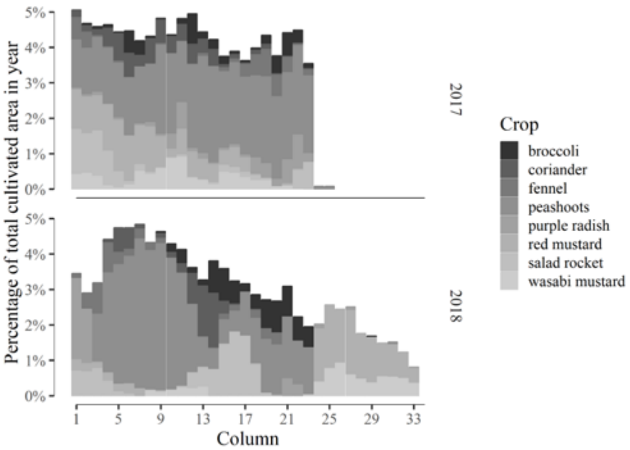
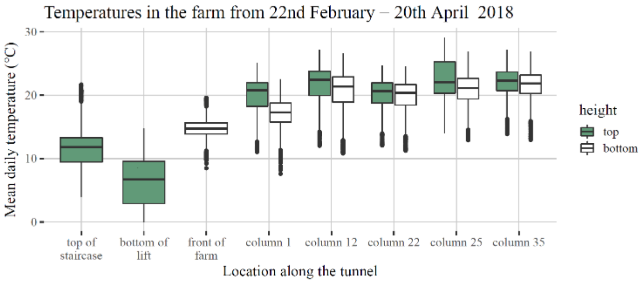
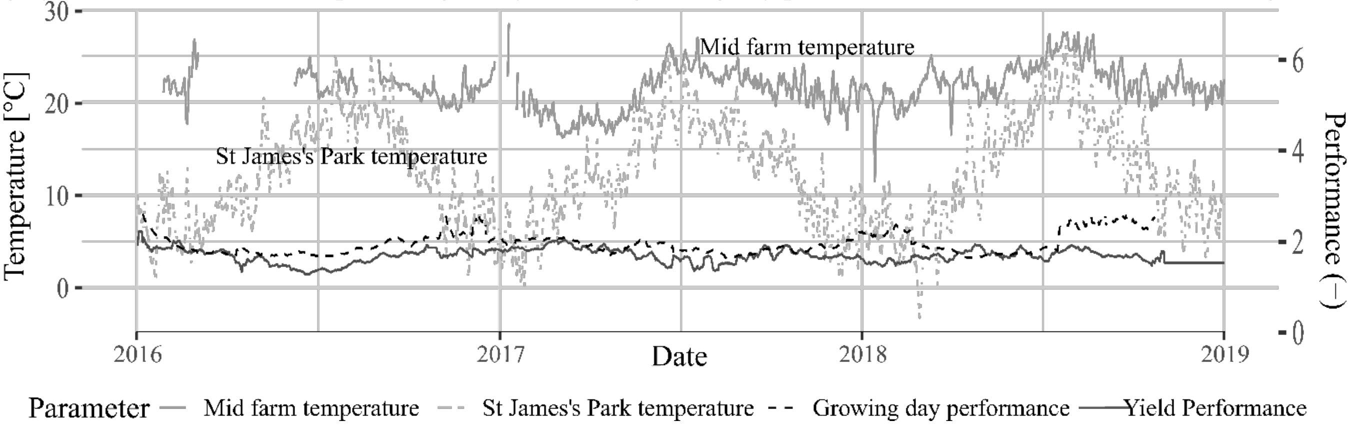


Figure 9 Temperature variation in the tunnel in Spring 2018. The height indicates the top or bottom shelf.



The number of growing days decreased when outdoor temperatures rose, whereas yields tended to be higher in winter. However, the data also suggests that each crop behaved differently and were not influenced by factors in the same way, but interpretations are limited as not all crops were grown in all conditions. At present, different crops are grown at positions along the tunnel based on available space and habit, rather than tailoring each crop location to their most suited environment (Figure 8). As a result, there is a bias in analysing location versus yield, as there are not as many datapoints for each crop at every location. This highlights the need for ongoing monitoring and regular data analysis in an operational farm, so that the impact of daily activities in the farm can be directly fed back to Growing Underground, and they can optimise the location where each crop is grown.

Figure 10 Temperature of St James' Park and in mean temperature in the middle of the farm (solid and dashed light grey lines – left hand axis), plotted against yield and growing day performance (solid dashed dark lines – right axis)



3.3 Predicting the impact of the weather on the farm environment

Weather conditions were found to affect temperature and humidity in the farm, energy use for the extraction fans and the number of growing days of the crops. Indeed, Figure 10 shows that as temperatures grew warmer over summer, the crops tended to grow faster to reach the same yields. At the same time, the overall yield is poorer in the summer, possibly due to it being too hot. Indeed, although it does get cooler than the lower bound of temperature in winter, crops tended to yield better, as the heat gained through the lighting system was enough to compensate for the cooler temperatures. This was not the case for the crops located near to the doors (columns 1-6 and 30-31 in Figure 7).

Because of this analysis, the crop yields were much better in summer 2018 than in the previous two summers, possibly due to better environmental management, with increased use of the extraction fan, carefully management of the doors for airflow and improved fan configurations (see next section).

3.3 Improving farm ventilation configuration

The monitoring data was also used to educate operational changes in the farm. For example, the high levels of relative humidity led to the installation of dehumidifiers. For example, adding perforated tubes over the plant trays increased the air velocity at the front of the tunnel (Figure 12a).

Figure 11 shows how the relative humidity was within the optimal range for longer periods in 2018 The black points show the average outdoor monthly humidity, which shows little variation year on year, but clearly influences the stability of the relative humidity in the farm across winter and summer. Even with decreased ventilation (lower ACH needed to minimise cold air intake) in winter, the relative humidity levels are higher in the farm than in summer.

Different configurations of fans were tested, to increase air mixing in the farm, such as snail fans along the sides, perforated tubes, central fans, and experimenting with the extraction fan levels. The ultimate configuration led to lesser horizontal and vertical variation of temperature. and more optimal air velocities around the farm (Figure 12b). This led to more even crop growth longitudinally along the tunnel, and higher CO_2 uptake from the air. For example, adding perforated tubes over the plant trays increased the air velocity at the front of the tunnel (Figure 12a).

Figure 11 Number of hours in a day that the relative humidity fell within optimal thresholds

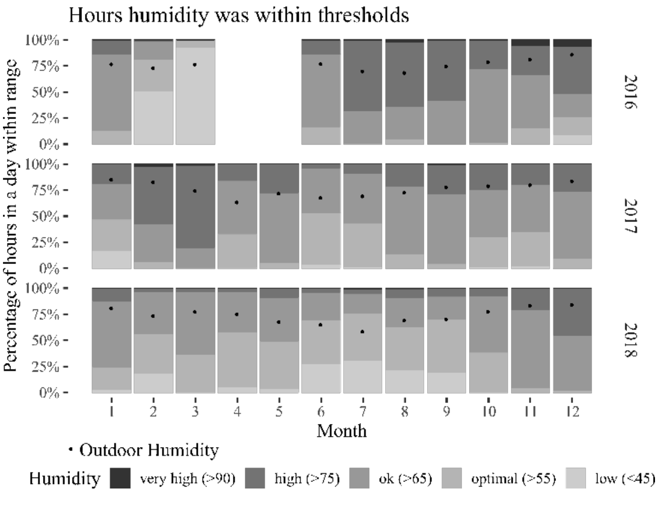
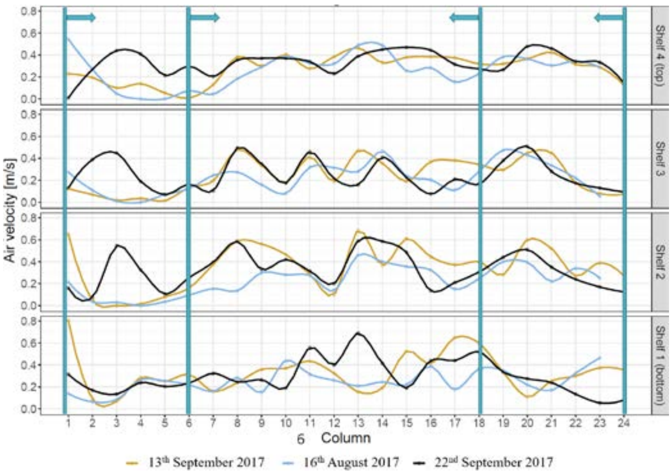
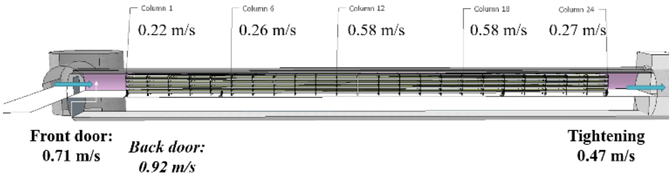


Figure 12

(12a) Point measurements of air current speed in Autumn 2017, with blue lines marking location of small fans with direction of airflow. Perforated tubes directing air flow over the trays were introduced 20th September.



(12b) Representative air velocities derived from measurements



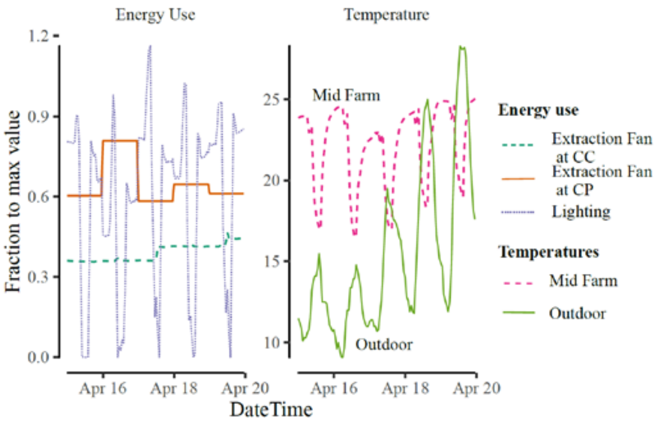
3.4 Optimising energy use

On average, the farm uses 56 kWh a day, and has two points of connection to the grid, at either end of the tunnel, known as Carpenters Place (CP) and Clapham Common (CC). The meter reading at CP can be used to derive the energy use for the first extraction fan, the baseload and the lighting. The second meter reading from CC is only linked to the second extraction fan.

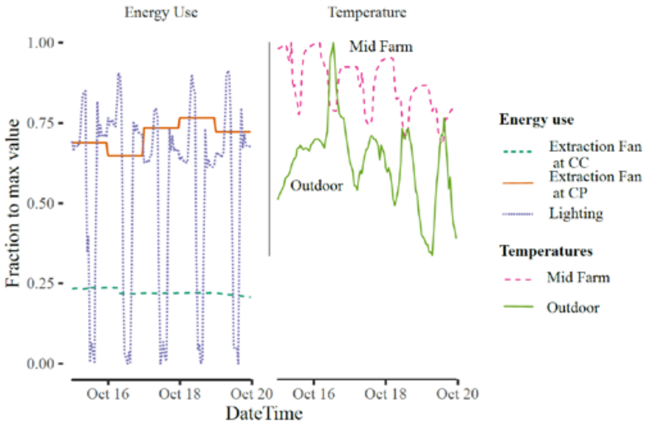
The data showed that the temperatures in the tunnel were strongly influenced by the waste heat gained through the lighting (shown in Figure 13). This information was used to advise GU on the air changes per hour (ACH) with the extraction fans, and optimizing their lighting period, not just for longer photo-period, but for maintaining optimal temperatures. The duration of the photo-period impacts farm temperatures, which need to kept low in summer, but higher in winter. Farm conditions are also strongly influenced by the extraction fan, where augmenting the cross-ventilation will increase crop growth in summer but decrease it in winter.

Figure 13 Energy use for the extraction fan and lighting and impact on temperature

(13a) Comparison for five days in April 2018 shows that the ventilation setting on the extraction fans is enough to avoid rising temperatures in the tunnel



(13b) Comparison for five days in October 2018 shows that as temperatures outside are dropping, the photoperiod could be lengthened to maintain temperatures in the farm, and the ventilation setting at CP could be reduced.



5. Conclusions

This data analysis demonstrates the first exercise in using the monitored data to assist Growing Underground to fine tune the environment of the farm. Different types of data collection were discussed: daily manual recording and wireless sensor networks, for three types of parameters: crop growth, environmental conditions, and operational controls. The data was combined and compared with each other to derive meaning and establish optimal environmental conditions, ventilation configurations, and understanding the effects of seasonality. This work has thus shown how monitoring can be developed for an urban farm in a derelict space, but also how performance indicators can be drawn out from different kinds of data, in order to assist the growth and limit the energy use in a hydroponic farm.

The longitudinal and ongoing data collection lends itself quite well to deriving data-centric models to forecast controls within the farm. There is a growing trend to fully automate greenhouse controls (Chaudhary, Nayse and Waghmare, 2011; Körner and Hansen, 2012; Kozai, 2016), however these systems are still in their infancy and require adept statistical models based on extended monitoring. The interpretations established in this paper will be developed further in a forecasting model to test future farm configurations for extension projects.

6. Acknowledgements

We thank the cooperation of Growing Underground with our work, and for enabling such a fruitful collaboration for so many years. Project funded by the EPSRC.

7. References

Advanticsys (2017) *IAQM-THCO2 | Wireless Temperature Monitoring | Modbus Indoor Air Quality Sensor*. Available at: https://www.advanticsys.com/shop/index.php?main_page=product_info&cPath=16&products_id=48 (Accessed: 14 January 2019).

Aqeel-ur-Rehman, Abbasi, A. Z., Islam, N. and Shaikh, Z. A. (2014) 'A review of wireless sensors and networks' applications in agriculture', *Computer Standards & Interfaces*. North-Holland, 36(2), pp. 263–270. doi: 10.1016/J.CSI.2011.03.004.

Benis, K., Reinhart, C. and Ferrao, P. (2017) 'Development of a simulation-based decision support workflow for the implementation of Building-Integrated Agriculture (BIA) in urban contexts', *Journal of Cleaner Production*, 147, pp. 589–602. doi: 10.1016/j.jclepro.2017.01.130.

Chaudhary, D. D., Nayse, S. P. and Waghmare, L. M. (2011) 'Application of Wireless Sensor Networks for Greenhouse Parameter Control in Precision Agriculture', *International Journal of Wireless & Mobile Networks (IJWMN)*, 3(1). doi: 10.5121/ijwmn.2011.3113.

Despommier, D. (2011) 'The vertical farm: Controlled environment agriculture carried out in tall buildings would create greater food safety and security for large urban populations', *Journal fur Verbraucherschutz und Lebensmittelsicherheit*, 6(2), pp. 233–236. doi: 10.1007/s00003-010-0654-3.

Garnett, T. (2013) 'Food sustainability: Problems, perspectives and solutions', *Proceedings of the Nutrition Society*, 72(1), pp. 29–39. doi: 10.1017/S0029665112002947.

Gemini Data Loggers (2018) *TinyTag Transit 2 | Temperature data logger for transportation, with a built-in sensor*, *Data Loggers*. Available at: https://www.geminidataloggers.com/data-loggers/tinytag-transit-2/tg-4080 (Accessed: 20 January 2019).

Körner, O., Aaslyng, J. M., Andreassen, A. U. and Holst, N. (2007) 'Microclimate prediction for dynamic greenhouse climate control', *HortScience*.

Körner, O. and Hansen, J. B. (2012) 'An on-line tool for optimising greenhouse crop production', *Acta Horticulturae*. doi: 10.17660/ActaHortic.2012.957.16.

Kozai, T. (2016) *Plant Factory - An Indoor Vertical Farming System for Efficient Quality Food Production*. Edited by T. Kozai, G. Niu, and M. Takagaki. Oxford, UK: Elsevier Inc.

Park, D.-H. and Park, J.-W. (2011) 'Wireless Sensor Network-Based Greenhouse Environment Monitoring and Automatic Control System for Dew Condensation Prevention', *Sensors*, 11(12), pp. 3640–3651. doi: 10.3390/s110403640.

Pons, O., Nadal, A., Sanyé-Mengual, E., Llorach-Massana, P., Cuerva, E., Sanjuan-Delmàs, D., Muñoz, P., Oliver-Solà, J., Planas, C. and Rovira, M. R. (2015) 'Roofs of the Future: Rooftop Greenhouses to Improve Buildings Metabolism', *Procedia Engineering*, 123, pp. 441–448. doi: 10.1016/j.proeng.2015.10.084.

Specht, K., Siebert, R., Hartmann, I., Freisinger, U. B., Sawicka, M., Werner, A., Thomaier, S., Henckel, D., Walk, H. and Dierich, A. (2013) 'Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings', *Agriculture and Human Values*, pp. 1–19. doi: 10.1007/s10460-013-9448-4.

van Straten, G. and Henten, E. J. van (2010) 'Optimal Greenhouse Cultivation Control: Survey and Perspectives', *IFAC Proceedings Volumes*. Elsevier, 43(26), pp. 18–33. doi: 10.3182/20101206-3-JP-3009.00004.

Tei, F., Scaife, A. and Aikman, D. P. (1996) 'Growth of Lettuce, Onion, and Red Beet. 1. Growth Analysis, Light Interception, and Radiation Use Efficiency', *Annals of Botany*. Oxford University Press, 78(5), pp. 633–643. doi: 10.1006/anbo.1996.0171.

Teitel, M., Atias, M. and Barak, M. (2010) 'Gradients of temperature, humidity and CO2 along a fan-ventilated greenhouse', *Biosystems Engineering*, 106(2), pp. 166–174. doi: 10.1016/j.biosystemseng.2010.03.007.

Thompson, H. C. and Langhans, R. W. (1998) 'Shoot and root temperature effects on lettuce growth in a floating hydroponic system', *Journal of the American Society for Horticultural Science*, 123(3), pp. 361–364. Available at: http://journal.ashspublications.org/content/123/3/361.full.pdf (Accessed: 9 August 2017).

Zero Carbon Foods Ltd (2017) *Growing Underground*. Available at: www.growing-underground.com (Accessed: 20 July 2011).