Chapter 7: Assessing the temperature variations in rooftop greenhouses in Tshwane and Johannesburg.

1. Introduction

As a final phase towards understanding the climate change adaptation (CCA) potential of retrofitting dense urban settings with building-integrated agriculture (BIA) initiatives, the study considered the potential of rooftop greenhouses (RTGs) to limit the exposure of the indoor environment to the expected climate change-driven temperature increases. Three climate change risks were identified in the literature review: a reduction in water security, increasing ambient temperatures and heat stress, and food insecurity. The study specifically considers the capacity of these RTGs to improve the indoor thermal environment as it represents a CCA strategy that can be undertaken by individual building owners with potentially immediate benefit for themselves as well as having concomitant benefits for the proximate context. In line with the pragmatism approach, this study specifically assessed the existing typologies that are implemented in the Johannesburg and Tshwane regions.

As third and final research objective, the study assesses the impact of BIA farms on the indoor thermal environment of buildings. As per the research protocol, the study documented the thermal performance of a series of RTGs located in Tshwane and Johannesburg. The collected microclimatic data were subsequently used to verify a digital model of a theoretical building located in Hatfield, Tshwane. The model enabled the simulation of the thermal performance of a building roof completely retrofitted with RTGs. While Chapters 7 and 8 collectively address the third research objective, Chapter 7 specifically discusses the data collected from the fieldwork.

While a series of BIA farm types have been identified in Chapter 6, the study specifically considers RTGs as the predominant BIA farm type located in Johannesburg and Tshwane. This farm type can be easily retrofitted to existing buildings (Sanyé-Mengual et al. 2015; Nadal et al. 2018). While there are a number of studies on the various forms of BIA; research into the benefits and impacts of RTGs is more recent and requires consideration in poorer developing contexts.

Few studies have considered the benefits of RTGs, specifically the use of integrated RTGs (Sanye-Mengual et al. 2018). Integrated RTGs can be defined as a BIA farm type that exchanges metabolic flows with the built environment to boost the efficiency of both the agriculture project and the associated building (Sanye-Mengual et al. 2018). Benis et al. (2015;

2017) considered the environmental impact, specifically energy, water consumption and carbon footprint of a series of BIA farm types. These include typical RTGs, integrated RTGs, vertical agriculture, and indoor food factories. Their study identified integrated RTGs as the most efficient in terms of resource consumption (Benis et al. 2017). Finally, Nadal et al. (2018) argue that in addition to the energy and resource gains, integrated RTGs present additional social and cultural benefits - if they are integrated with the appropriate building function.

It is important to note that while the above-mentioned studies all consider integrated RTGs, the RTGs documented in this study are less integrated with the built environment. These test sites were identified due to their proximity and adjacency to the built environment, as well as presenting two types of RTGs implemented in South Africa at the time of the study.

The sites were located in Johannesburg (n=4) and Tshwane (n=1). The fieldwork was undertaken in both the summer and winter periods and the sites were documented for a minimum of five consecutive days at a time. Due to the limited number of sensors available and as the study documented five sites during both the hottest and coldest periods, the fieldwork was limited to between five to ten consecutive days per site. A similar documentation period was used by Taleghani et al. (2014). The study documented ambient temperature (T_a), relative humidity (RH), and globe temperature (T_g) in two locations inside and one outside the RTGs.

This chapter starts by discussing the findings from each documented site. Following the discussion on the findings, the chapter considers the general microclimatic performance of the farm type and how the design resolution, material choice, and spatial context impact its performance.

2. Analysis findings

2.1. Characteristics of test sites

A selection of five sites was documented during the analysis. Four of the five sites follow similar construction and planting strategies, while the fifth site is located in Tshwane and follows a different approach. See Table 29 for details pertaining to each site.

The context and location of the sites vary. While they are all located in dense formal urban contexts, the four sites in Johannesburg are located in medium to higher density urban conditions (Figures 64-67). On the other hand, the farm located in Tshwane is situated in a lower-to-medium built density neighbourhood (Figure 68).

Figure 64: De Hoofd Mansions Farm, Johannesburg.

Figure 65: Minerals Council Farm, Johannesburg.

Figure 66: New Gate Mall Farm, Johannesburg.

Figure 67: Stanop Building Farm, Johannesburg.

Figure 68: A Good Year Farm, Tshwane.

The farms are located at various levels above ground level, ranging from 3 – 7 storeys (maximum 25m height). Their surrounding context also differs. One of the farms, the Stanop building farm, is completely exposed to high wind and solar conditions, while the others are all protected to varying degrees (Table 29). The farm that experiences the most overshadowing is the Newgate Mall farm that is overshadowed on the eastern and western sides by adjacent buildings, while the building on the northern face allows sunlight in but still provides wind protection.

Four of the five farms all use the same greenhouse and planting technology. The farms employ simple decentralised nutrient film technique (NFT) hydroponic systems, with the crops planted on A-frame structures (Figure 69). The greenhouses are vaulted structures, built from galvanised steel circular hollow sections, and covered with a Poly-Ethylene Vinyl Acetate (Poly-EVA) sheeting and a 40% green high-density polyethylene (HDPE) shade netting on top to limit the UV damage to the plants. The fifth farm, located in Tshwane, only uses 40% HDPE shade netting and employs a vertical soil-based planting system.

Figure 69: Typical greenhouse and planting systems of both types of test sites.

All the farms were newly constructed during the time of the study. There were limited signs of damage to the structures. A few of the farms have to accommodate existing infrastructure on the roofs, resulting in a series of poorly sealed envelopes. The greenhouse doors were also often kept open as an attempt to cool the structures in the summer periods, while during the winter periods all the openings were closed.

Table 29: Technological, spatial and contextual characteristics of the test sites.

	A Good Year (AGY) Farm	De Hoofd Mansions (DHM) farm	Minerals Council (MC) farm	Newgate Mall (NM) Farm	Stanop Building (SB) farm
Location	Brooklyn, Tshwane.	New Doornfontein, JHB.	Marshall Town, JHB.	Central Business district, JHB.	New Doornfontein, JHB.
Element Retrofitted	Portion of parking garage.	Portion of building roof.	Balcony.	Portion of building roof.	Portion of building roof.
Level of farm	3rd floor	7th floor	7th floor	4th floor	8th floor
Building Occupancy	Retail, parking.	Mixed use – Housing, retail (ground level).	Offices.	Retail, parking.	Mixed use – Light industrial, educational.
Context and Surround built density	Medium density commercial.	Medium to high density – housing and light industrial	High density commercial	High density commercial and housing	Medium to high density – housing and light industrial
Greenhouse Exposure – Solar	No overshadowing, low level sunlight overshadowed on eastern and western edges	Western elevation shaded	Western edge shaded, 1m balcony surround	Limited overshadowing on western, northern and eastern sides	All sides exposed
Greenhouse Exposure – Wind	Eastern, western and southern faces protected	Western face protected	Western edge protected, 1m balcony surround	Eastern, western and northern faces protected	All sides exposed
Technology – Greenhouse	40% HDPE shade netting fixed to galvanised steel framed structure.	40% HDPE shade netting with white pigmented Poly-EVA sheeting fixed to galvanised steel framed structure.			
Technology – Planting system	Vertical soil-based system with drip-irrigation liquid nutrient system.	NFT hydroponic system. A-frame planting structure.			
Produce type	Leafy greens – bok choy, lettuces, coriander, spinach, basil, fennel.	Leafy greens - various lettuces	Mint, lemon balm, basil.	Leafy greens – Lettuces, basil	Leafy greens - Lettuces, basil, coriander.

2.2. Analysis of Ambient temperatures, Relative Humidity and Globe temperatures

The experiment tested whether the RTGs contribute to microclimatic variations. This was tested at three locations, positioned on the southern and northern edges inside the RTGs, and one outside the RTGs on the open roofs. The hypothesis proposes that there is a difference between the RTG interior and the exterior microclimatic conditions.

2.2.1. A Good Year farm, Tshwane

The winter period analysis of *A Good Year* farm (AGY farm), revealed the following. The descriptive statistics of the temperature variations (T_a) report a limited difference between the three locations. As indicated in Table 30 the mean T_a of the north ($T_{a\ mean}$ = 15.85°C; $T_{a\ sd}$ = 7.54°C), south ($T_{a\ mean}$ =14.23°C; $T_{a\ sd}$ = 6.77°C) and open ($T_{a\ mean}$ = 14.01°C; $T_{a\ sd}$ = 4.96°C) locations were very similar, with the northern location reaching a maximum T_a (34.9°C) that was close to 11K more than that of the open location. The interior locations also logged the lowest minimum T_a conditions.

The relative humidity (RH) conditions also presented limited variations between the three locations. The southern location revealed a slightly higher mean RH (RH_{mean} = 56.28%; RH_{sd} = 21.57%), while the RH_{mean} of the northern location was the lowest, being marginally lower than the open location (Table 30). The T_g analysis reported a slightly lower mean T_g for the southern location ($T_{g\ mean}$ = 14.80°C; $T_{g\ sd}$ = 7.14°C) than the open ($T_{g\ mean}$ = 16.54°C; $T_{g\ sd}$ = 9.72°C) and northern locations ($T_{g\ mean}$ = 16.52°C; $T_{g\ sd}$ = 7.99°C). On the other hand, the standard deviation of both the northern and southern locations was less than the open location, pointing towards a more stable indoor environment in terms of the T_g conditions.

Table 30: Descriptive statistics of the Winter Ta, RH and Tg readings - AGY farm.

	Location	N Obs	Mean	Std Dev	Median	Minimum	Maximum
Ambient Temperature (°C)	North	361	15.85	7.54	13.00	6.30	34.90
	South	361	14.23	6.77	11.50	6.60	31.90
	Open	362	14.01	4.96	12.70	7.10	23.80
Relative Humidity (%)	North	361	50.62	21.90	49.70	17.50	95.50
	South	361	56.28	21.57	57.50	14.40	97.30
	Open	361	51.96	23.65	50.80	13.90	99.90
Globe Temperature (°C)	North	361	16.52	7.99	13.30	6.70	33.90
	South	361	14.80	7.14	11.90	6.90	31.80
	Open	361	16.54	9.72	11.70	5.20	36.80
Abbreviations:	N Obs – Number of observations Std Dev – Standard Deviation						

The visual display analysis revealed that the RTG interior experienced the highest T_a conditions during the hottest periods of the day (Figure 70). The T_g conditions followed very similar patterns, but during periods of high insolation much higher T_g conditions occurred at the open location (Figure 71). The remainder of the time the T_g conditions at the various locations corresponded closely.

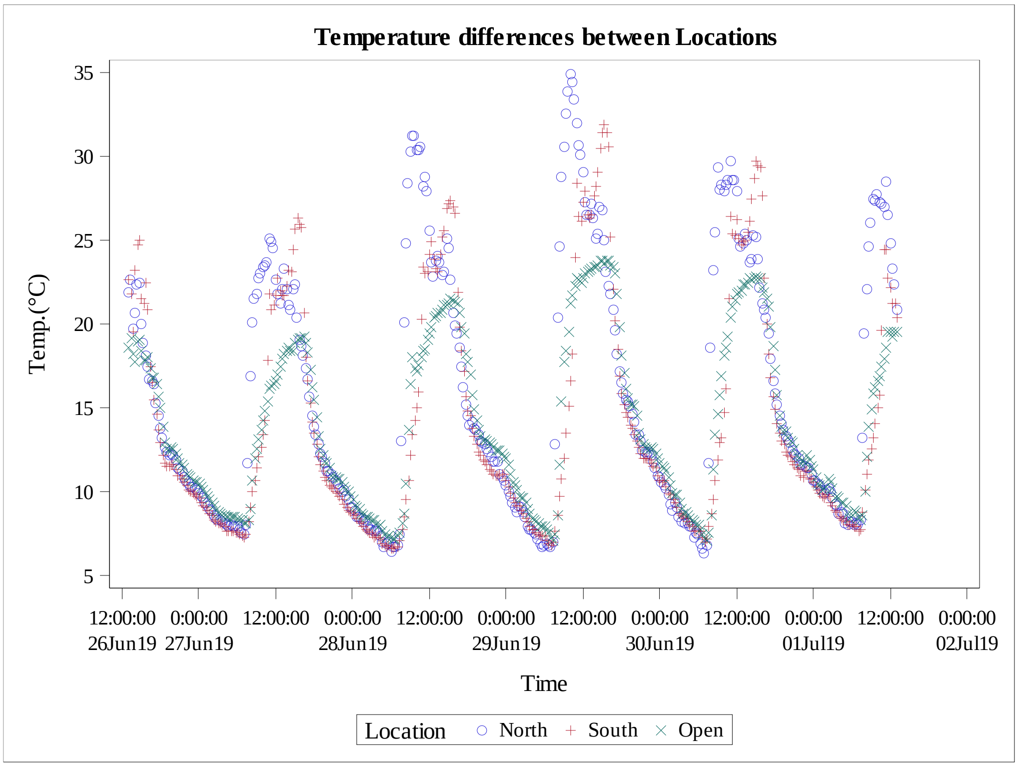

Figure 70: Winter Ambient Temperature (Ta) differences between the locations – AGY farm.

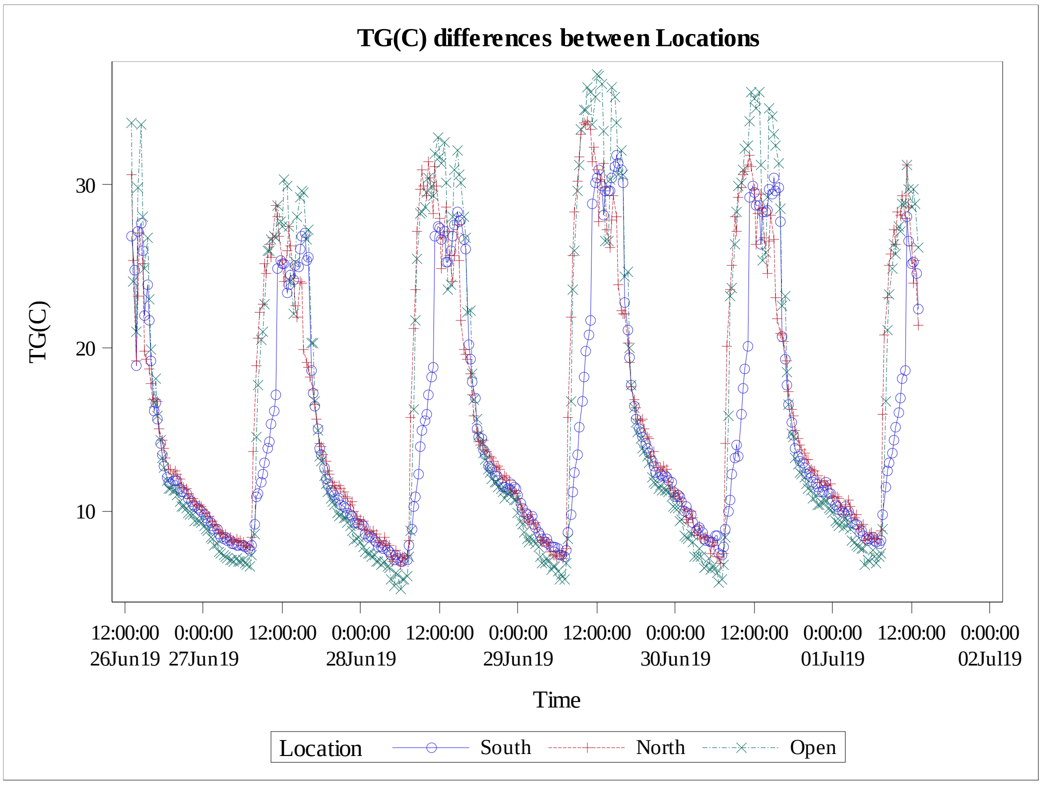

Figure 71: Winter Globe Temperature (Tg) differences between the locations – AGY farm.

An Analysis of variance (ANOVA) test was performed for all three parameters. In all three cases, T_a (T_a DF = 1082; T_a F-value = 8.65; T_{ap} = 0.0002), RH (RH DF = 1082; RH F-Value = 6.31; RH_p = 0.0019) and T_g (T_g DF = 1082; T_g F-value = 5.16; T_{gp} = 0.0059), the p-values rejected the null hypothesis on 95% confidence value. A 95% confidence level is generally considered an adequate indication of statistically significant findings (Caldwell 2010). While statistically significant Ta, RH and Tg variations were documented, the effect size of these respective variations can be considered small (Tar^2 = 0.0157; RHr^2 = 0.00115; Tgr^2 = 0.009). The ANOVA analysis revealed that in the winter conditions the RTG modulates the internal conditions but to a limited extent.

The Bonferroni (Dunn) test considered the groupings of the various data findings. The findings revealed two data groupings. In terms of T_a conditions, a consistent variation was found between the northern and southern locations of the greenhouse, with the southern location correlating closely with the open location (Table 31). Conversely, the T_g and RH measurements reveal a higher similarity between the northern and open locations. The findings point towards the formation of two zones in the RTG that perform differently and that one of the zones correlates closer with the open conditions.

Table 31: Bon grouping of the three parameters measured in the winter period – AGY farm.

T_a – Bon Grouping				**RH – Bon Grouping**				**T_g – Bon Grouping**			
	Mean	**N**	**LOC**		**Mean**	**N**	**LOC**		**Mean**	**N**	**LOC**
A	15.8540	361	North	A	56.280	361	South	A	16.5418	361	Open
								A			
B	14.2260	361	South	B	51.960	361	Open	A	16.5158	361	North
B				B							
B	14.0094	361	Open	B	50.615	361	North	B	14.8000	361	South
**Means with the same letter are not significantly different.*											
Abbreviations:				N – Number of observations LOC– Location							

During the summer period a slight variation in the overall performance was documented. The descriptive statistics reveal limited variations in terms of the mean T_a conditions with the open location ($T_{a\ mean}$ = 28.94°C; $T_{a\ sd}$ = 7.49°C) having the highest mean temperature followed by north ($T_{a\ mean}$ = 27.97°C; $T_{a\ sd}$ = 6.71°C), and finally south ($T_{a\ mean}$ = 27.82°C; $T_{a\ sd}$ =

6.49°C) (Tabel 32). The analysis further revealed that the minimum T_a temperatures were generally very similar, and the highest maximum T_a conditions were recorded in the open location. In terms of the T_g conditions the open location ($T_{g\ mean}$ = 32.02°C, $T_{g\ sd}$ = 11.74°C) also documented the highest $T_{g\ mean}$ and $T_{g\ max}$ readings (open $T_{g\ max}$ = 53.30°C). The T_g conditions of the northern ($T_{g\ mean}$ = 29.74; $T_{g\ sd}$ = 9.27°C) and southern locations ($T_{g\ mean}$ = 29.80; $T_{g\ sd}$ = 9.13°C) were very similar. In terms of the RH parameter the three locations closely aligned, with the open location presenting a slightly lower RH_{mean} (33.75%) as summarised in Table 32.

Table 32: Descriptive statistics of the Summer Ta, RH and Tg readings - AGY farm.

	Location	**N Obs**	**Mean**	**Std Dev**	**Median**	**Minimum**	**Maximum**
Ambient Temperature (°C)	North	421	27.97	6.71	27.30	15.70	39.50
	South	421	27.82	6.49	27.20	15.50	40.00
	Open	421	28.94	7.49	28.10	15.90	41.80
Relative Humidity (%)	North	421	36.13	20.71	30.00	10.30	95.70
	South	421	35.70	21.01	29.00	10.40	97.00
	Open	421	33.75	21.10	27.90	8.60	93.20
Globe Temperature (°C)	North	421	29.74	9.27	28.10	15.20	47.10
	South	421	29.80	9.13	26.90	15.30	46.80
	Open	421	32.02	11.74	28.60	15.60	53.30
Abbreviations:	N Obs – Number of observations Std Dev – Standard Deviation						

In contrast, the visual analysis revealed that at the open location the T_a conditions were consistently warmer in summer (Figure 72), particularly during the hottest period of the day (Figure 72). This demonstrates that the RTG is an effective shading device during periods of high insolation. The results from the visual analysis of the T_g data corroborate the findings showing a consistently cooler indoor environment at mid to late afternoon (Figure 73).

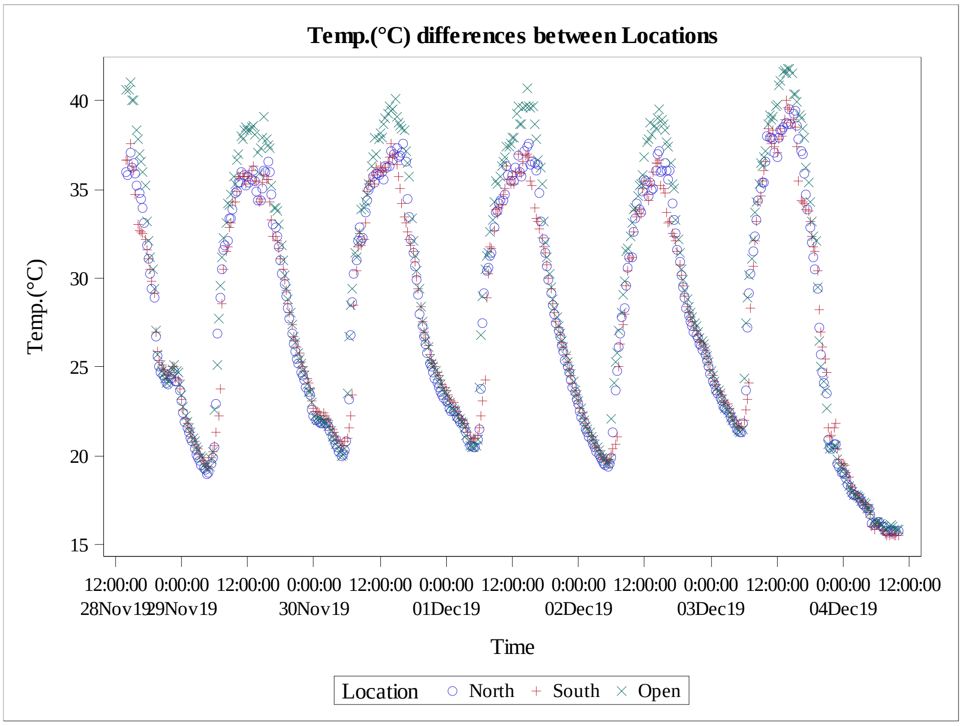

Figure 72: Summer Ambient Temperature (Ta) differences between the locations - AGY farm.

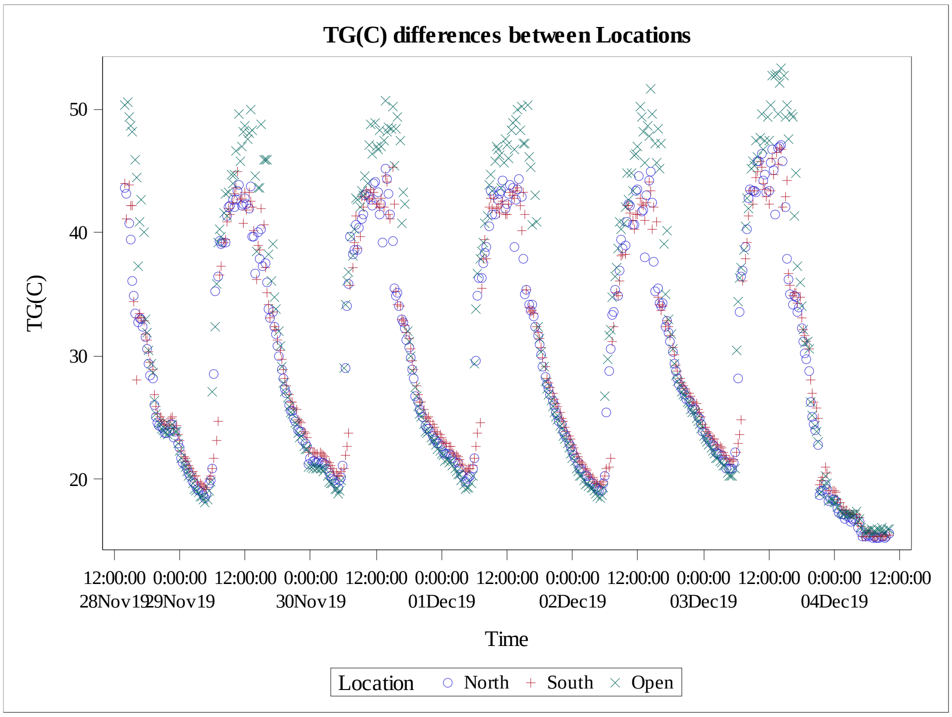

Figure 73: Summer Globe Temperature (Tg) differences between the locations – AYG farm.

The ANOVA test revealed that in the summer period there was a statistically significant variation of the T_a and T_g conditions between the three locations – T_{ap} = 0.039 (T_a DF = 1262; T_a F-value = 3.23) and T_{gp} = 0.0010 (T_g DF = 1262; T_g F-value = 6.92) respectively. Importantly, it is noted that the effect size of the variations is very small ($T_a r^2$=0.0051; $T_g r^2$=0.0103). The

RH data failed to reject the null hypothesis (RH DF = 1262; RH F-value = 1.55; RH_p=0.2123), confirming little variation between the RTG interior and the exterior RH conditions. A Bonferroni (Dunn) test revealed limited variations, with a single grouping for the T_a and RH parameters (Table 33). Only the T_g parameter indicated a clear grouping between the locations, pointing towards the T_g conditions of the RTG interior being significantly lower than the exterior.

Table 33: Bon grouping of the parameters measured in the summer period - AGY Farm.

T_a – Bon Grouping				**RH – Bon Grouping**				**T_g – Bon Grouping**			
	Mean	**N**	**LOC**		**Mean**	**N**	**LOC**		**Mean**	**N**	**LOC**
A	28.9378	421	Open	A	36.133	421	North	A	32.0154	421	Open
A				A							
A	27.9696	421	North	A	35.700	421	South	B	29.8019	421	South
A				A				B			
A	27.8242	421	South	A	33.747	421	Open	B	29.7378	421	North
**Means with the same letter are not significantly different.*											
Abbreviations:				N – Number of observations LOC– Location							

In contrast to temperature variations identified in the visual analysis, the majority of the temperatures aligned closely. On the other hand, in the summer season cooler indoor conditions were documented during the hottest periods of the study (Figure 72). This supports the evidence that the RTG covered with a 40% HDPE shade netting leads to cooler temperatures in summer and slightly warmer conditions in winter during peak heating periods. While these season-specific phenomena were documented during the hottest periods of the day, it is important to note that none of the thermal energy was retained at night when lower temperatures were experienced. The RH remained similar throughout with the winter period documenting a significant, but small, variation between the three locations.

Importantly, during the winter period the RTG had two microclimatic zones, with one zone reflecting the outdoor T_a, RH and T_g conditions. On the other hand, the summer period showed little differentiation between the zones. As a result, the RTG provides little thermal modulation during hotter periods.

2.2.2. De Hoofd Mansions Farm, Johannesburg

De Hoofd Mansions (DHM) farm was only documented for the winter period. Unfortunately the farm burned down in October 2019 due to an electrical fault. As a result, only winter data is available for analysis.

The descriptive statistics of the winter data revealed a clear variation between the T_a conditions of open ($T_{a\ mean}$ = 13.19°C; $T_{a\ sd}$ = 4.38°C) and south ($T_{a\ mean}$ = 13.72°C; $T_{a\ sd}$ = 5.16°C) and the northern locations ($T_{a\ mean}$ = 16.99°C; $T_{a\ sd}$ = 10.02°C). The data also showed highly variable T_a conditions in the northern location as well as much higher $T_{a\ max}$ conditions, being 14.20K higher (Table 34). The RH parameter revealed less variation between the locations with the southern location experiencing the highest mean RH (RH_{mean} = 38.87%) (Table 34). Finally, the T_g conditions were more varied, the northern location ($T_{g\ mean}$ = 17.74°C, $T_{g\ sd}$ = 11.04°C) had the highest mean T_g conditions, followed by the open location ($T_{g\ mean}$ = 15.31°C; $T_{g\ sd}$ = 9.11°C). The southern location ($T_{g\ mean}$ = 14.27; $T_{g\ sd}$ = 5.49°C) experienced the lowest mean T_g conditions and variations (Table 34).

Table 34: Descriptive statistics of the Winter Ta, RH, and Tg readings - DHM farm.

	Location	N Obs	Mean	Std Dev	Median	Minimum	Maximum
Ambient Temperature (°C)	North	361	16.99	10.02	12.00	5.30	35.10
	South	361	13.72	5.16	12.90	6.70	24.40
	Open	361	13.19	4.38	13.00	6.10	20.90
Relative Humidity (%)	North	362	35.13	17.25	36.60	9.90	79.30
	South	362	38.87	12.95	37.40	15.70	71.70
	Open	361	37.31	14.87	36.60	12.80	77.90
Globe Temperature (°C)	North	361	17.74	11.04	12.10	5.40	37.20
	South	361	14.27	5.49	13.20	6.80	26.50
	Open	361	15.31	9.11	11.20	3.70	35.30
Abbreviations:	N Obs – Number of observations Std Dev – Standard Deviation						

The visual analysis of the DHM farm data also revealed that the T_a and T_g variations were prevalent during the hottest periods of the day (Figure 74 & Figure 75). It shows that the T_a parameters of the northern location experience significant temperature variations, while this occurs to a lesser extent at the southern location. In terms of the T_g parameter, the northern and open locations experienced high thermal increases during the early midday to late afternoon periods, while the southern location was much more moderate in its thermal amplitudes (Figure75). During the cooler night-time periods, the T_a conditions were often cooler inside the RTG than outside, while in terms of the T_g parameters the indoor conditions were slightly warmer.

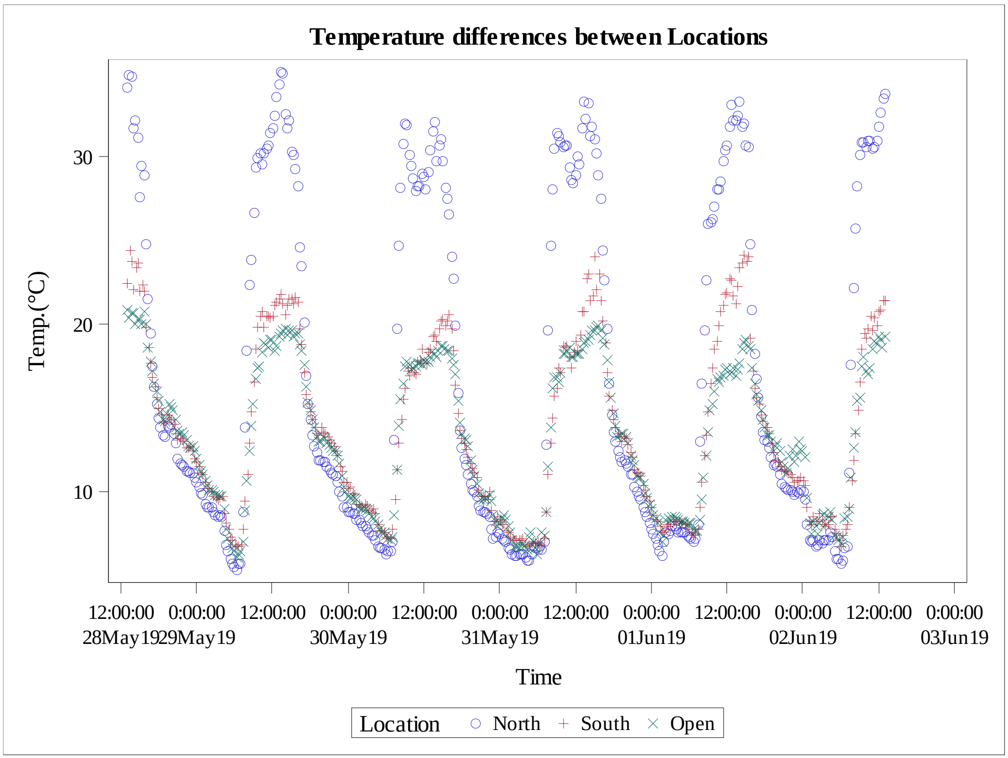

Figure 74: Winter Ambient temperature (Ta) differences between locations - DHM farm.

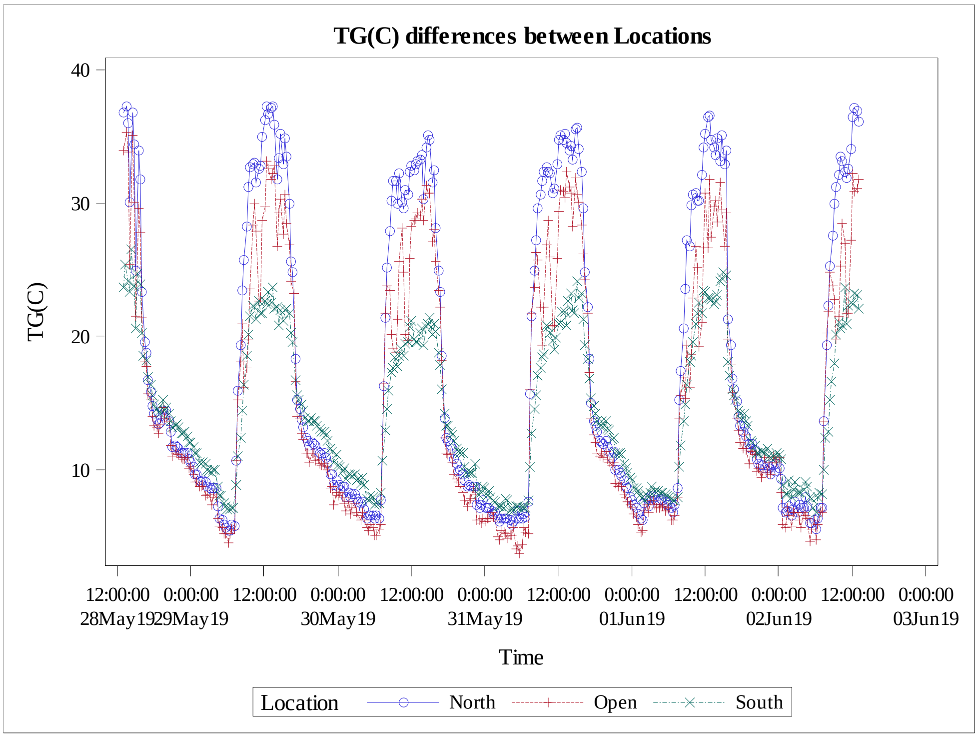

Figure 75: Winter Globe temperature (Tg) differences between locations - DHM farm.

The ANOVA test results for the three parameters, T_a (T_a DF = 1082; T_a F-Value = 31.33; T_{ap} = 0.0001), RH (RH DF = 1082; RH F-value = 5.56; RH_p = 0.0039), and T_g, (T_g DF = 1082; T_g F-value = 14.56; $T_{gp} < 0.0001$) rejected the null hypothesis, confirming that there were T_a, RH and T_G variations between the three locations. Yet the effect size of these three parameters varied. The variations in T_a are considered medium ($r^2 = 0.054$), while RH and T_g variations are small ($RHr^2 = 0.0101$; $TGr^2 = 0.0262$).

The Bonferroni (Dunn) test analysis confirmed the visual analysis findings that the T_a and T_g variances are primarily attributed to fluctuations in the northern zone of the RTG. In Table 35 the grouping shows that the closest T_a and T_g correlations are between the southern and open locations, revealing high temperature variations in the RTG itself, as well as limited control to create a homogenous indoor environment. In terms of the RH conditions there seems to be more overlap both between the northern and open locations, and the southern and open locations. While there are overlaps, two distinct groupings are retained in the RH parameter.

Table 35: Bon grouping of the three parameters measured in the winter period – DHM farm.

T_a – Bon Grouping				**RH – Bon Grouping**					**T_g – Bon Grouping**			
	Mean	**N**	**LOC**			**Mean**	**N**	**LOC**		**Mean**	**N**	**LOC**
A	16.9853	361	North		A	38.865	361	South	A	17.7352	361	North
					A							
B	13.7152	361	South	B	A	37.307	361	Open	B	15.3061	361	Open
B				B					B			
B	13.1911	361	Open	B		35.127	361	North	B	14.2731	361	South
**Means with the same letter are not significantly different.*												
Abbreviations:				N – Number of observations LOC– Location								

The findings reveal that the RTG modulates the microclimate to a small/medium extent. Furthermore, the northern zone of the greenhouse performs very differently to the southern zone. While the visual display confirms a limited degree of variation, it shows the thermal variations are most pronounced during the hottest periods of the day, while at night the lower indoor and outdoor conditions correlate closely.

2.2.3. Minerals Council Farm, Johannesburg

The analysis of the Minerals Council (MC) farm's microclimatic conditions during the summer and winter periods revealed the following. In terms of the T_a parameter, the descriptive statistics revealed a minimal variation in the mean and maximum T_a conditions (Table 36). The northern ($T_{a\ mean}$ = 12.45°C; $T_{a\ sd}$ = 4.36°C) and the open locations ($T_{a\ mean}$ = 12.84°C; $T_{a\ sd}$ = 4.58°C) both revealed higher mean T_a temperatures while the southern side ($T_{a\ mean}$ = 11.50°C; $T_{a\ sd}$ = 5.72°C) of the RTG was on average cooler but exhibit the highest maximum T_a conditions (Table 36). Importantly, the lowest indoor T_a conditions were only 1.5K warmer than outside (1.70 vs 0.20°C).

The analysis of the RH indicated that the RTG achieved a much higher mean RH for the interior (North: RH_{mean} = 54.4%; RH_{sd} = 13.48%; South: RH_{mean} = 53.27%; RH_{sd} = 15.55%) than documented in the open location (RH_{mean} = 38.42%; RH_{sd} = 12.61%). The T_g analysis revealed that the performance of the three locations corresponds, with south ($T_{g\ mean}$ = 12.04°C; $T_{g\ sd}$ = 6.30°C) experiencing the highest thermal amplitudes with more extreme maximum and minimum T_g conditions than north ($T_{g\ mean}$ = 12.73°C; $T_{g\ sd}$ = 5.28°C) and open ($T_{g\ mean}$ = 12.96°C; $T_{g\ sd}$ = 4.50°C). The open location still exhibited the lowest minimum T_g conditions of 1.20°C.

Table 36: Descriptive statistics of the Winter Ta, RH, and Tg readings - MC farm.

	Location	N Obs	Mean	Std Dev	Median	Minimum	Maximum
Ambient Temperature (°C)	North	362	12.45	4.36	11.40	4.00	22.70
	South	362	11.50	5.72	9.70	1.70	25.40
	Open	367	12.84	4.58	12.50	0.20	23.40
Relative Humidity (%)	North	361	54.41	13.48	57.00	23.70	79.50
	South	361	53.27	15.55	55.00	20.30	87.50
	Open	366	38.42	12.61	37.40	16.80	84.00
Globe Temperature (°C)	North	361	12.73	5.28	11.20	3.70	25.50
	South	361	12.04	6.30	9.90	1.80	27.80
	Open	366	12.96	4.50	12.30	1.20	22.30
Abbreviations:	N Obs – Number of observations Std Dev – Standard Deviation						

The visual analysis of the T_a and T_g conditions revealed that during the colder periods the RTG interior was consistently cooler than the open location. Conversely, during the hottest periods the southern side of the RTG was significantly warmer than the outdoor measured temperatures (Figures 76 & 77). The visual analysis of the RH conditions corroborated the fact that the greenhouse achieves consistently higher RH conditions indoors, with dramatic fluctuations at around noon daily (Figure78).

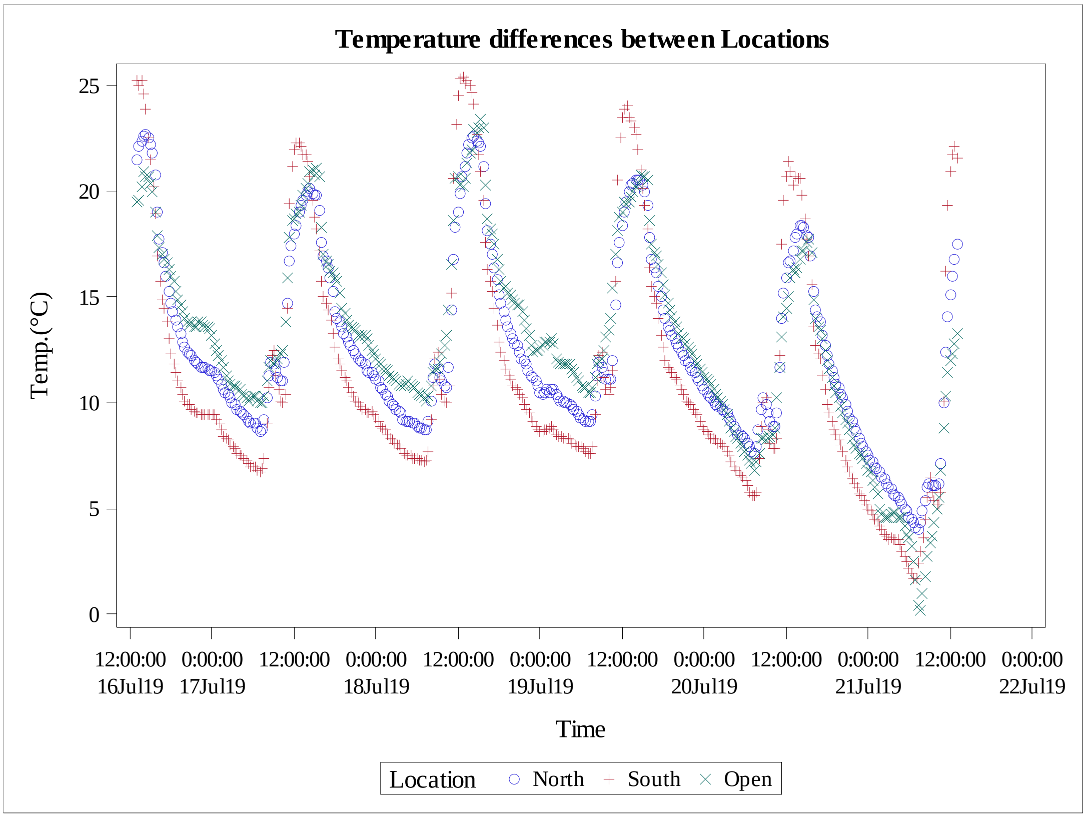

Figure 76: Winter Ambient Temperature (Ta) variable differences between the locations – MC farm.

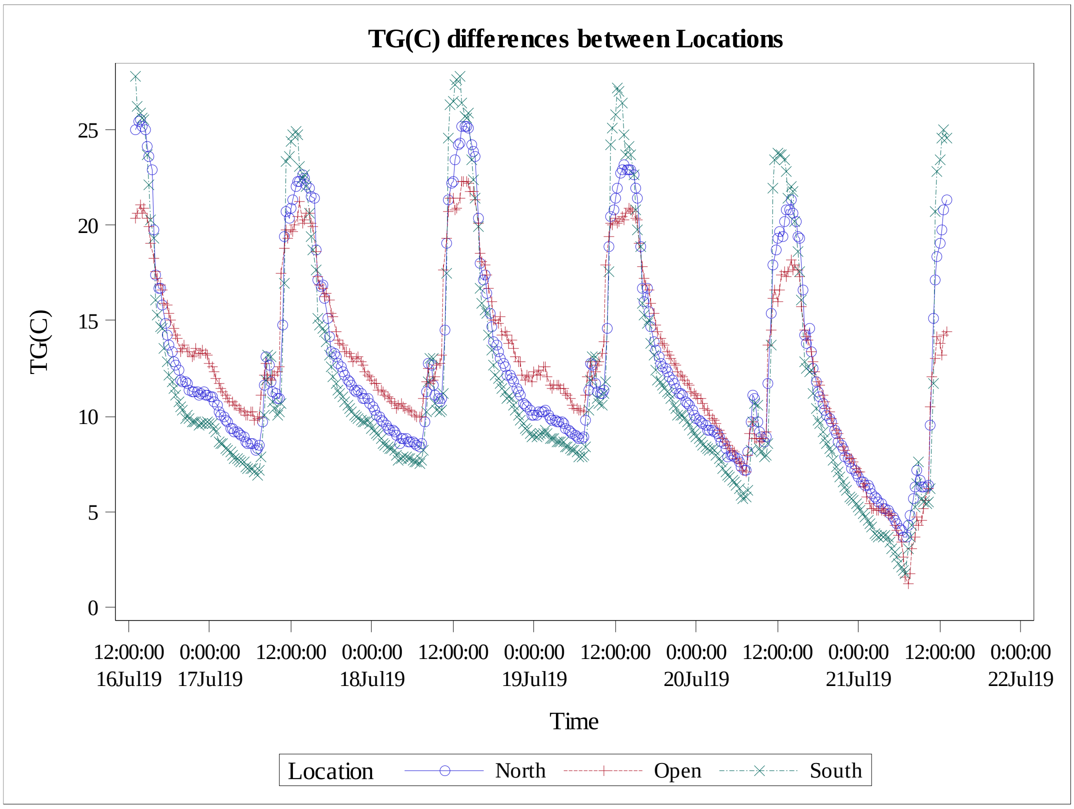

Figure 77: Winter Globe Temperature (Tg) variables differences between the locations – MC farm.

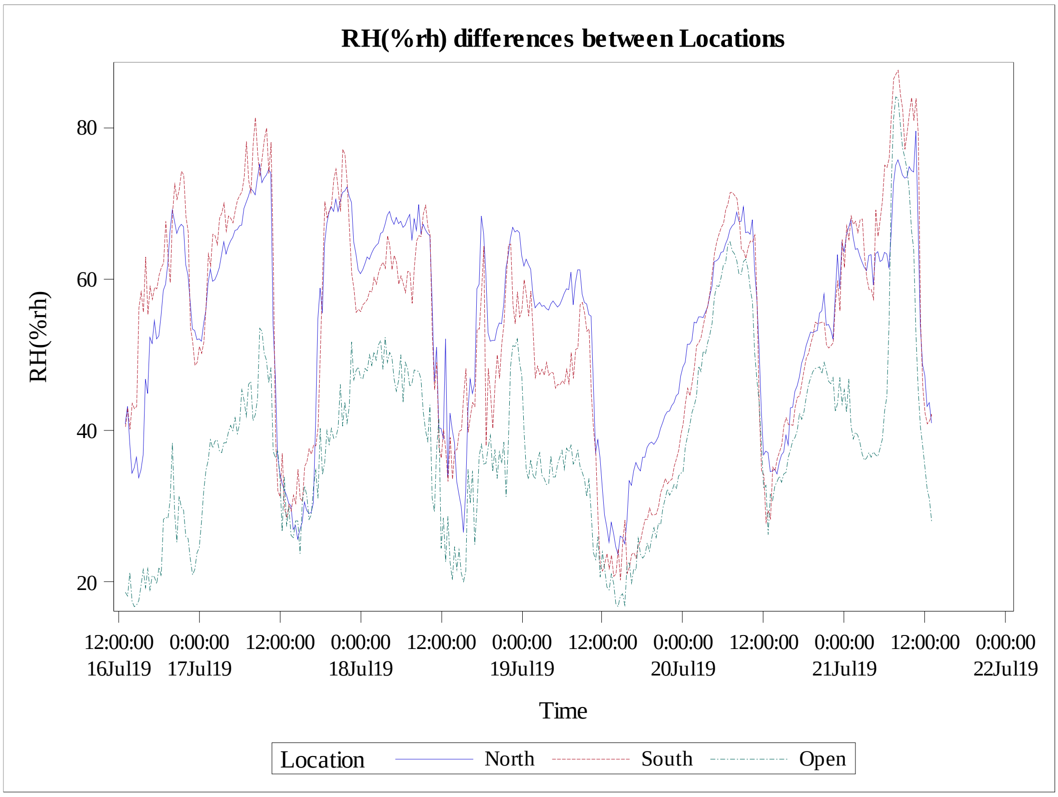

Figure 78: Winter Relative Humidity (RH) variables differences between the locations – MC farm.

The ANOVA test revealed that statistically there was a variation in the T_a (T_a DF = 1082; T_a F-value = 7.07; T_{ap} = 0.0009) and RH conditions (RH DF = 1082; RH F-value = 147.99; RH_p < 0.0001) by rejecting the null hypothesis. The effect size of the Ta variations is small (Tar^2 = 0.012); conversely the effect size of the RH variations is large (RHr^2 = 0.215). In term of the T_g parameters, the ANOVA test findings failed to reject the null hypothesis (T_g DF = 1082; T_g F-value = 2.81; T_{gp} = 0.0605), and therefore did not reveal statistically significant variations between the three locations (95% confidence interval).

The effect size of the RH parameter indicates a large variation, which corroborates the visual analyses; the T_a parameter needs closer consideration. While the effect size of the T_a parameters is smaller, the visual assessment revealed points where the T_a variations are significant. In this instance this occurred during periods of high outdoor temperatures and high insolation levels (Figure 76). As a result, the findings point to the fact that the RTG does not stabilise the indoor T_a temperature effectively, but escalates higher thermal conditions.

Finally, the Bonferroni (Dunn) test revealed, similarly to the DHM farm, that in terms of the T_a parameter the largest variation was between the northern and southern locations (Table 37). This similarly concludes that there is limited thermal control within the farm and neither does the farmer manage to stabilise and achieve a generally ameliorated thermal condition. In terms of the RH conditions, the Bonferroni grouping points towards the interior of the greenhouse being significantly more humid than the exterior conditions (Table 37). It is an important finding as this is the only RTG that manages to achieve higher indoor RH conditions, which can result in optimised growing conditions and lower water consumption through evapotranspiration (Peet 1999).

Table 37: Bon grouping of the three parameters measured in the winter period - MC Farm.

T_a – Bon Grouping				RH – Bon Grouping				T_g – Bon Grouping			
	Mean	**N**	**LOC**		**Mean**	**N**	**LOC**		**Mean**	**N**	**LOC**
A	12.8432	361	Open	A	54.413	361	North	A	12.9557	361	Open
A				A				A			
A	12.4524	361	North	A	53.267	361	South	A	12.7255	361	North
								A			
B	11.5039	361	South	B	38.416	361	Open	A	12.0380	361	South
**Means with the same letter are not significantly different.*											
Abbreviations:				N – Number of observations LOC– Location							

The summer data of the T_a (T_a DF = 1019; T_a F-value = 1.11; T_{ap} = 0.33) and T_g (T_g DF = 1019; T_g F-value = 0.03; T_{gp} = 0.97) conditions for the MC farm failed to reject the null hypothesis, indicating that statistically there was no variation between the T_a and T_g variables of the three locations. As a result, the Bonferroni (Dunn) test revealed no grouping between the various locations for these parameters. In terms of the RH conditions, statistical relevant variations were recorded, $RH_p < 0.0001$ (RH DF = 1019; RH F-value = 103.58). The effect size of these variations can also be considered large (RHr^2 = 0.169), although less than what was documented during the winter period.

While the descriptive statistics confirmed the lack of T_a and T_g variations, and a high degree of similarity between the different locations (Table 38), Figure 79 reveals that the southern and northern locations had consistently cooler minimum T_a temperatures than the exterior conditions. The visual analysis pointed towards lower T_a and T_g conditions inside the RTG during the cooler periods in summer. While the T_g variations are negligible for the MC farm, the visual display revealed that the RTG manages to maintain lower interior T_g conditions (Figure 80).

Table 38: Descriptive statistics of the Summer Ta, RH, and Tg readings – MC farm.

	Location	N Obs	Mean	Std Dev	Median	Minimum	Maximum
Ambient Temperature (°C)	North	340	23.92	6.00	21.85	16.30	36.00
	South	340	23.25	6.92	20.60	14.70	37.30
	Open	340	23.78	5.48	22.15	15.60	37.20
Relative Humidity (%)	North	340	61.05	16.17	59.55	21.80	89.30
	South	340	63.70	18.36	61.50	21.80	95.50
	Open	340	45.27	19.47	40.65	13.70	88.40
Globe Temperature (°C)	North	340	25.32	8.02	21.95	16.10	43.20
	South	340	25.18	10.03	20.65	14.20	48.00
	Open	340	25.21	8.13	22.50	15.70	54.20
Abbreviations:	N Obs – Number of observations Std Dev – Standard Deviation						

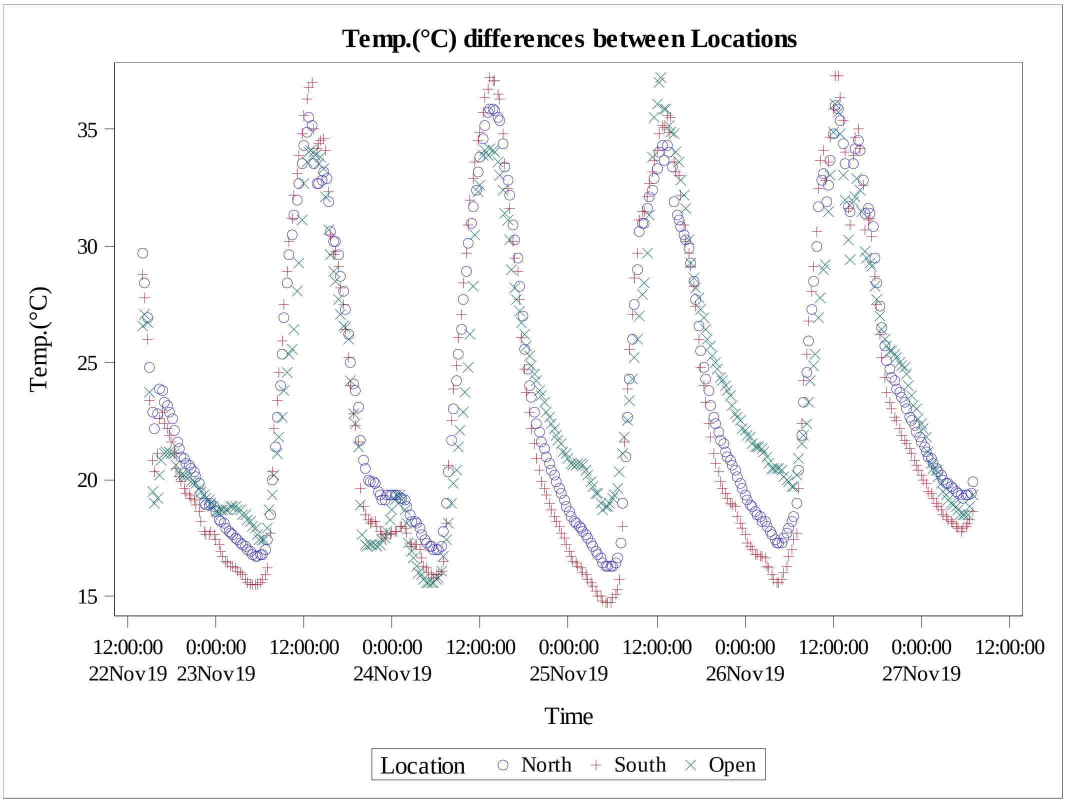

Figure 79: Summer Ambient temperature (Ta) differences between the locations - MC farm.

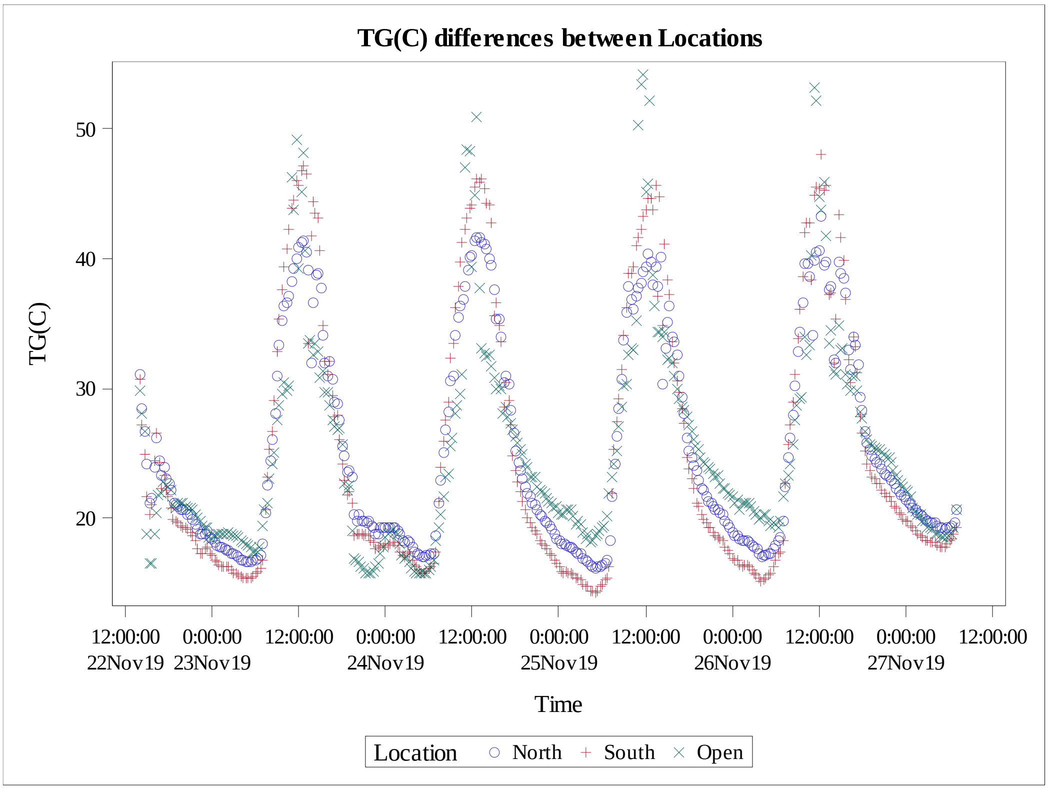

Figure 80: Summer Globe Temperature (Tg) differences between the locations – MC farm.

On the other hand, the RH was still much higher within the RTG than outdoor conditions, with north (RH_{mean} = 61.05%; RH_{sd} = 16.17%) and South (RH_{mean} = 63.70%; RH_{sd} = 18.36%) correlating closely (Table 38). The Bonferroni (Dunn) test confirmed these trends, identifying two distinct groups being the RTG's interior and the outdoor conditions (Table 39).

Table 39: Bon grouping of the three parameters measured in the summer period – MC farm.

T_a – Bon Grouping				RH – Bon Grouping				T_g – Bon Grouping			
	Mean	**N**	**LOC**		**Mean**	**N**	**LOC**		**Mean**	**N**	**LOC**
A	23.9182	340	North	A	63.703	340	South	A	25.3247	340	North
A				A				A			
A	23.7791	340	Open	A	61.046	340	North	A	25.2071	340	Open
A								A			
A	23.2518	340	South	B	45.269	340	Open	A	25.1774	340	South
**Means with the same letter are not significantly different.*											
Abbreviations:				N – Number of observations LOC– Location							

The analysis of the MC farm RTG revealed a structure that provides a limited degree of thermal control. At times the indoor T_a conditions were much higher than the outdoor temperatures, while during the hotter summer periods the globe temperature (T_g) conditions experienced limited thermal modulation. Conversely, the RTG seemed to control the indoor relative humidity very effectively, contrary to the other examples, and achieved a much higher RH indoors.

2.2.4. Newgate Mall farm, Johannesburg

The analysis of the three parameters at the Newgate mall (NM) farm yielded diverse results. The descriptive statistical analyses of the winter data revealed that the mean T_a conditions between the three locations, open ($T_{a\ mean}$ = 13.27°C; $T_{a\ sd}$=3.62°C), south ($T_{a\ mean}$ = 13.36°C; $T_{a\ sd}$ = 7.62°C), and north ($T_{a\ mean}$ = 14.02°C; $T_{a\ sd}$ = 9.63°C), were very similar, but the standard deviation between the three points differed significantly (Table 40). The northern location experienced a temperature variation of up to 2.7 times the open location. Furthermore, the $T_{a\ max}$ difference between the northern and open locations was 14.8K (Table 40).

In terms of the T_g variations, the conditions of the three locations closely aligned. The mean T_g temperatures differed slightly between the northern ($T_{g\ mean}$ = 14.33°C; $T_{g\ sd}$ = 9.89°C), southern ($T_{g\ mean}$ = 13.64°C; $T_{g\ sd}$ = 8.12°C), and open locations ($T_{g\ mean}$ = 13.45°C; $T_{g\ sd}$ = 7.99°C) (Table 40). Furthermore, the maximum T_g conditions were also more aligned with each other. The descriptive statistics of the three locations' RH measurements were also very similar (Table 40).

Table 40: Descriptive statistics of the Winter Ta, RH, and Tg readings - NM farm.

	Location	N Obs	Mean	Std Dev	Median	Minimum	Maximum
Ambient Temperature (°C)	North	274	14.02	9.63	9.30	5.00	35.50
	South	274	13.36	7.62	9.80	5.50	29.50
	Open	273	13.27	3.62	12.80	6.30	20.70
Relative Humidity (%)	North	273	51.14	25.08	47.90	14.30	94.50
	South	273	49.49	22.72	45.30	14.80	90.40
	Open	273	45.49	23.37	39.50	12.60	99.30
Globe Temperature (°C)	North	271	14.33	9.89	9.60	5.30	36.80
	South	271	13.64	8.12	9.90	5.60	31.80
	Open	271	13.45	7.99	10.60	4.60	34.90
Abbreviations:	N Obs – Number of observations Std Dev – Standard Deviation						

The visual display analysis of the T_a data clearly indicates a pattern of extensive thermal gain and loss taking place during both the hottest and coldest periods of the day (Figure 81). This revealed a concerning trend whereby the RTG itself increased the daily indoor thermal amplitude, resulting in a much higher standard deviation (Table 40). Similar trends were also evident in the T_g data, with the highest temperature variations taking place during the hottest period of the day (Figure 82).

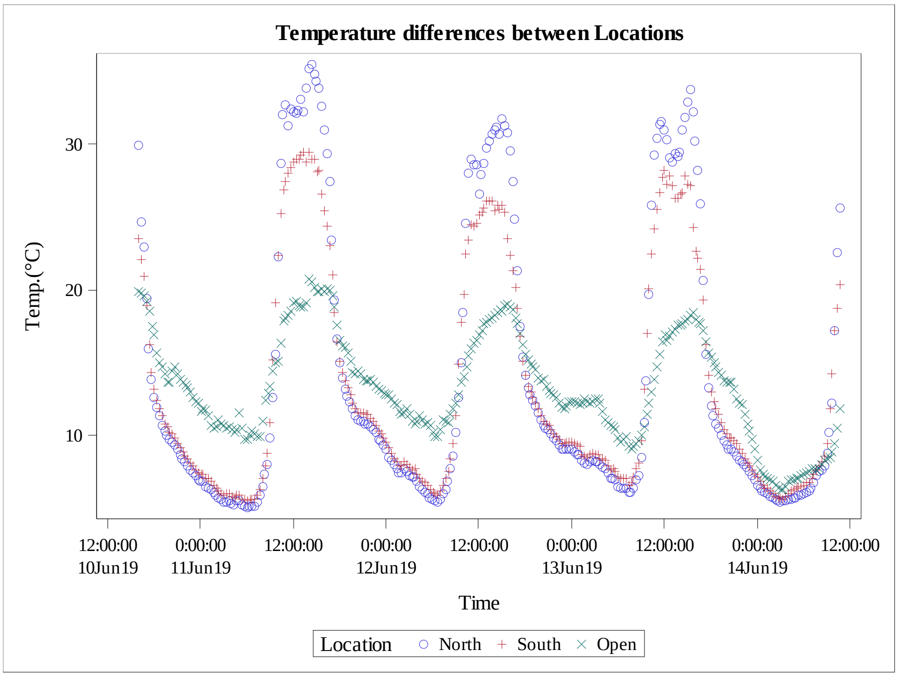

Figure 81: Winter Ambient Temperature (Ta) variations between locations - NM farm.

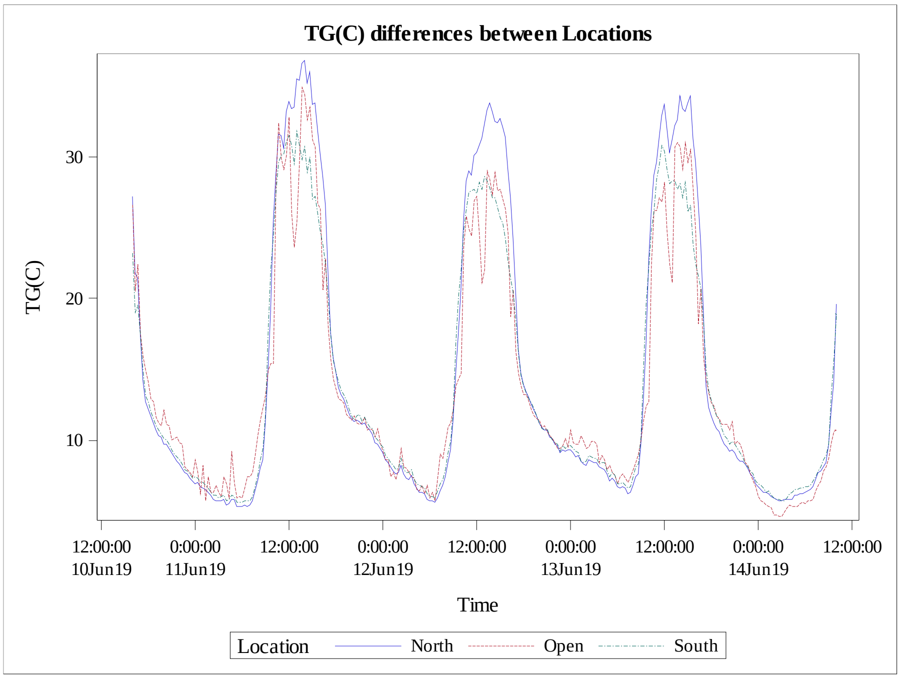

Figure 82: Winter Globe temperature (Tg) variations between locations - NM farm.

In terms of the ANOVA test a different set of findings was generated. The statistical analyses of T_a (T_a DF = 818; T_a F-value = 0.84; T_{ap} = 0.43) and T_g (T_g DF = 812; T_g F-value = 0.78; T_{gp} = 0.459) parameters revealed that the data fail to reject the null hypothesis. The test concluded that there was no statistical difference between the T_a and T_g conditions measured at the three locations. As a result the Bonferroni (Dunn) test concluded that there are no subgroups between the various points, substantiating the argument that there is no statistical difference between the locations (Table 41). The findings from the ANOVA test on the RH performance of the RTG rejected the null hypothesis (RH_p = 0.0173; RH DF = 818; RH F-value = 4.08), yet effect size of the variance is small (RHr^2 = 0.0098) supporting the descriptive statistics findings. The Bonferroni (Dunn) test analysis of the RH conditions indicated that there are two overlapping groups. As a result, the southern location shares similar RH conditions with both the northern and open locations (Table 41).

Table 41: Bon grouping for the three parameters measured in the winter period - NM farm.

T_a – Bon Grouping				**RH – Bon Grouping**					**T_g – Bon Grouping**			
	Mean	**N**	**LOC**			**Mean**	**N**	**LOC**		**Mean**	**N**	**LOC**
A	14.0220	273	North		A	51.138	273	North	A	14.3328	271	North
A					A				A			
A	13.3612	273	South	B	A	49.489	273	South	A	13.6376	271	South
A				B					A			
A	13.2700	273	Open	B		45.495	273	Open	A	13.4450	271	Open
**Means with the same letter are not significantly different.*												
Abbreviations:				N – Number of observations LOC– Location								

The summer data set for the three parameters, ambient temperature (T_a DF = 839; T_a F-value = 0.60; T_{ap} = 0.549), relative humidity (RH DF = 839; RH F-value = 0.45; RH_p = 0.638), and globe temperature (T_g DF = 839; T_g F-value = 0.31; T_{gp} = 0.733), all failed to reject the null hypothesis. As a result, it can be argued, with 95% confidence, that there is no statistical difference between the T_a, RH and T_g conditions measured at the northern, southern and open locations. Similarly, the Bonferroni (Dunn) test revealed no subgroupings between the different measured variables (Table 42).

Table 42: Bon grouping for the three parameters measured in the summer period - NM farm.

T_a – Bon Grouping				RH – Bon Grouping				T_g – Bon Grouping			
	Mean	**N**	**LOC**		**Mean**	**N**	**LOC**		**Mean**	**N**	**LOC**
A	25.4943	280	South	A	50.860	280	Open	A	27.8329	280	North
A				A				A			
A	25.4171	280	North	A	49.414	280	North	A	27.6900	280	Open
A				A				A			
A	24.7829	280	Open	A	49.369	280	South	A	27.1107	280	South
**Means with the same letter are not significantly different.*											
Abbreviations:				N – Number of observations LOC– Location							

Contrary to the winter data, descriptive analysis of the summer data revealed more homogenous T_a measurements at the three locations. There was a close correlation between the north ($T_{a\ mean}$ = 25.42°C; $T_{a\ sd}$ = 8.64°C), south ($T_{a\ mean}$ = 24.49°C; $T_{a\ sd}$ = 8.91°C), and open locations ($T_{a\ mean}$ = 24.78°C, $T_{a\ sd}$ = 7.75°C) (Table 43). The maximum T_a in the RTG interior reached higher temperatures than what was measured outside the RTG. In this case we noted the temperature variations during the daily peak temperature period at noon (Figure 83). Corresponding with the T_a data, the T_g parameters were also very similar in terms of their mean and standard deviations. It is important to note that the maximum globe temperatures were slightly higher indoors than outdoors (north: $T_{g\ max}$ = 53.20°C; south: $T_{g\ max}$ = 51.00°C; open: $T_{g\ max}$ = 49.30°C). Furthermore, the maximum T_g conditions on the roof were very high. Discussions with the various farmers revealed that these high temperatures often translate into very high root core and nutrient mix temperatures that inhibit nutrient uptake and subject the plants to intense stress conditions (Respondent 09, 12/04/2018).

Table 43: Descriptive statistics of the summer Ta, RH, and Tg readings – NM farm.

	Location	N Obs	Mean	Std Dev	Median	Minimum	Maximum
Ambient Temperature (°C)	North	280	25.42	8.64	22.35	14.10	43.30
	South	280	25.49	8.91	22.65	14.00	43.90
	Open	280	24.78	7.75	23.00	13.70	38.90
Relative Humidity (%)	North	280	49.41	19.14	48.95	14.60	82.20
	South	280	49.37	21.90	47.70	11.20	85.20
	Open	280	50.86	22.39	47.90	12.80	93.70
Globe Temperature (°C)	North	280	27.83	11.85	22.45	13.80	53.20
	South	280	27.11	10.73	23.10	13.90	51.00
	Open	280	27.69	11.85	22.35	12.70	49.30
Abbreviations:	N Obs – Number of observations Std Dev – Standard Deviation						

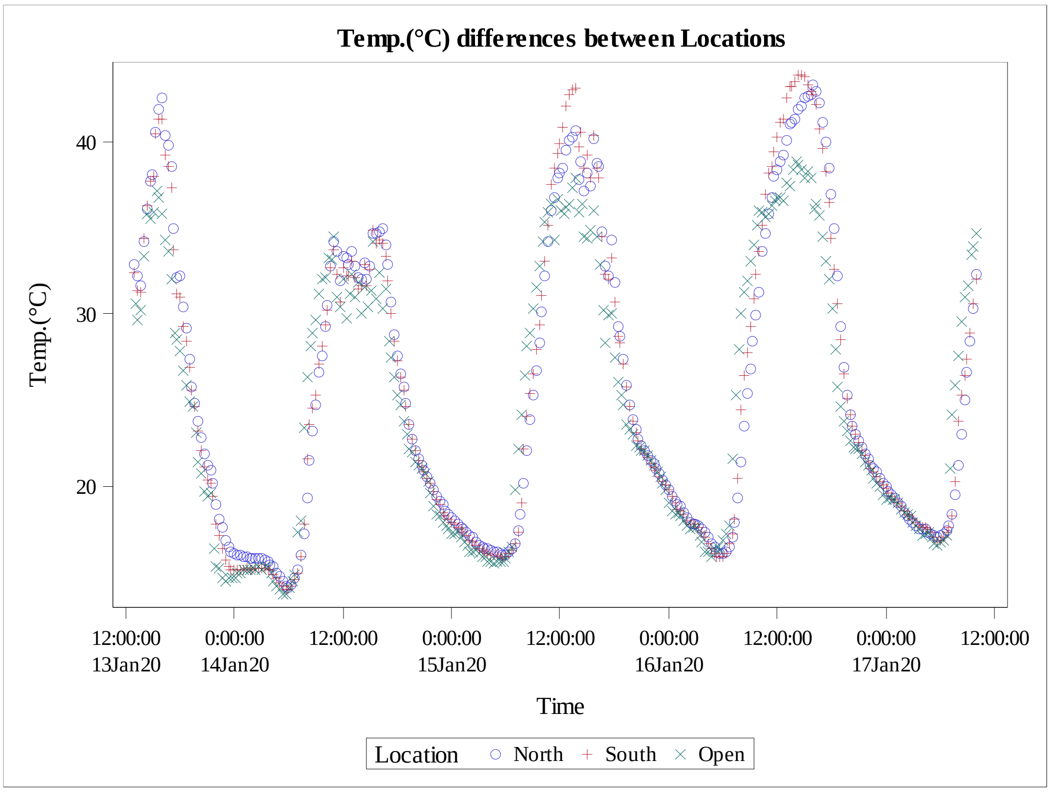

Figure 83: Summer Ambient Temperatures (Ta) differences between locations - NM farm.

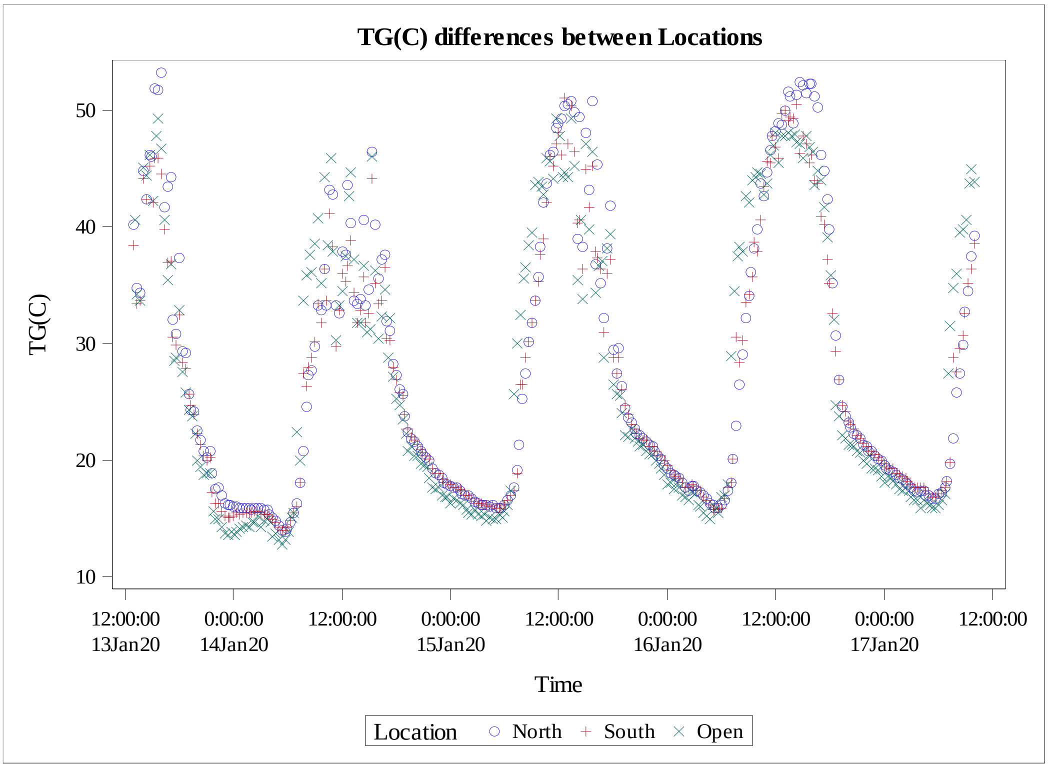

Figure 84: Summer Globe temperature (Tg) differences between locations - NM farm.

The analysis of Newgate Mall farm indicated that there was no statistical difference between the indoor and the outdoor environmental conditions. The RTG structure, therefore, has a limited capacity to control the indoor environment for improved crop outputs. As the construction material of this RTG is similar to all the other RTGs, except for the AGY farm, the site and surrounding conditions, as well as management practices of the RTG, potentially cause these similar microclimatic conditions.

2.2.5. Stanop Building farm, Johannesburg

The Stanop Building (SB) farm was the final site that was documented. It is the most exposed RTG of all the sites (Table 29). The descriptive statistics of the winter T_a data revealed similar trends as documented at the NM farm, but the T_a temperature variations were more modulated, resulting in comparable T_a conditions in the north ($T_{a\ mean}$ = 16.990°C; $T_{a\ sd}$ = 6.76°C), south ($T_{a\ mean}$ = 15.35°C; $T_{a\ sd}$ = 5.63°C), and open locations ($T_{a\ mean}$ = 14.32°C; $T_{a\ sd}$ = 3.91°C) (Table 44). While the mean T_a conditions were very similar to each other, the northern locations' standard deviation was more pronounced (Table 44). Finally, the $T_{a\ max}$ difference between north and open was extensive at 12.30K (34.00 vs 21.70°C).

The RH conditions showed little variation between the three locations, being north (RH_{mean} = 29.76%; RH_{sd} = 12.78%), south (RH_{mean} = 31.25%; RH_{sd} = 12.68%), and open (RH_{mean} = 31.19%; RH_{sd} = 14.25%) (Table 44). As per the T_g conditions similar mean and standard deviations were derived from the analysis, while the north ($T_{g\ max}$ = 31.40°C) and open locations ($T_{g\ max}$ = 35.30°C) both experienced much higher thermal conditions than the southern location ($T_{g\ max}$ = 27.60°C).

Table 44: Descriptive statistics of the Winter Ta, RH, and Tg readings - SB farm.

	Location	N Obs	Mean	Std Dev	Median	Minimum	Maximum
Ambient Temperature (°C)	North	361	16.90	6.76	15.00	6.30	34.00
	South	361	15.35	5.63	13.90	5.50	25.30
	Open	362	14.35	3.91	14.30	5.80	21.70
Relative Humidity (%)	North	361	29.76	12.78	29.90	9.60	74.40
	South	361	31.25	12.68	30.50	11.80	77.40
	Open	362	31.19	14.25	30.10	10.90	83.40
Globe Temperature (°C)	North	361	16.99	6.64	14.90	6.40	31.40
	South	361	15.88	6.23	14.10	5.40	27.60
	Open	361	15.87	8.44	12.70	3.70	35.30
Abbreviations:	N Obs – Number of observations Std Dev – Standard Deviation						

Similar to the other farms, the visual display of the T_a conditions also revealed a specific period of significant temperature variations. As in the other cases, this occurred at the hottest period of the day, during which the RTG accentuated the already warmer thermal conditions (Figure 85). A slight variation was found in the T_g analysis which showed that the outdoor location experienced higher T_g conditions at the hottest periods of the day (Figure 86).

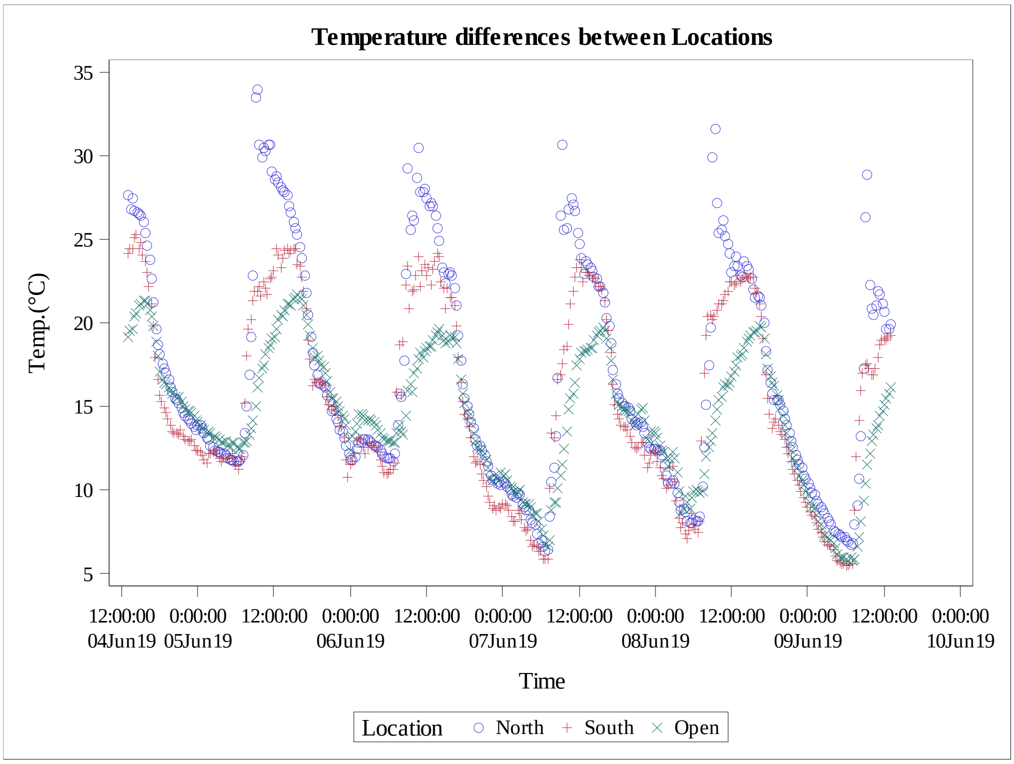

Figure 85: Winter Ambient temperature (Ta) differences between locations – SB farm.

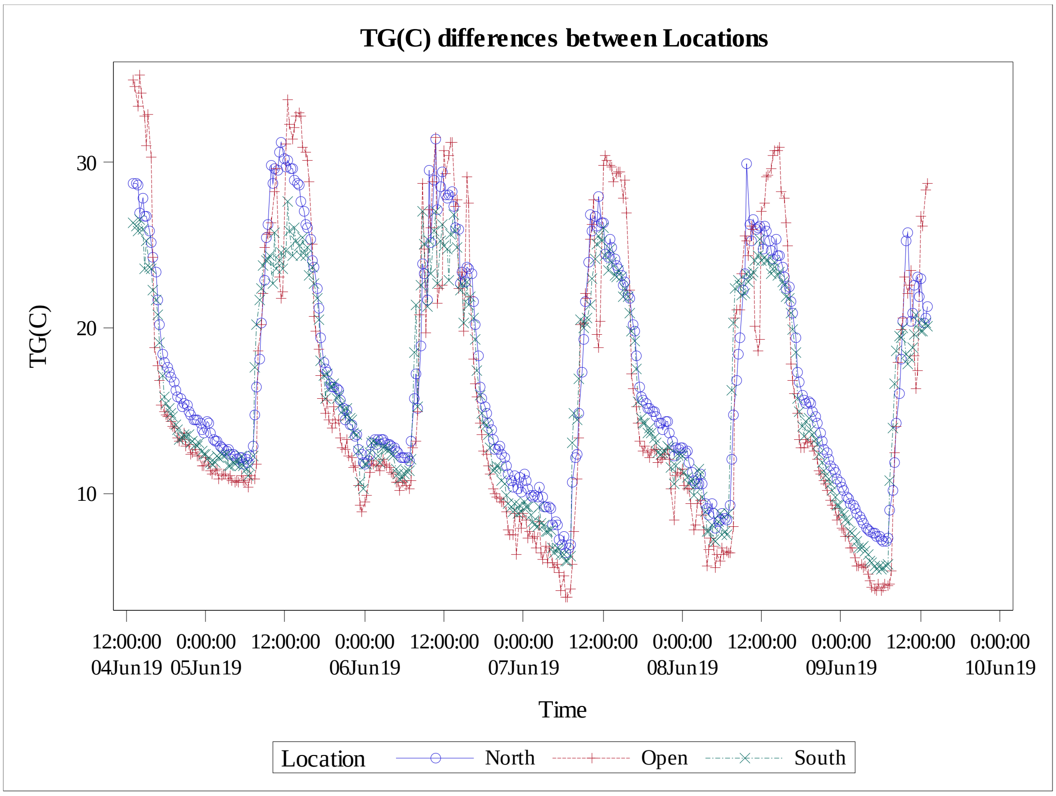

Figure 86: Winter Globe Temperature (Tg) differences between locations – SB farm.

The ANOVA test performed on the three parameters revealed that the T_a (T_a DF = 1082; T_a F-value = 19.34; $T_{ap} < 0.0001$) and T_g (T_g DF = 1082; T_g F-value = 2.95; $T_{gp} = 0.0528$) conditions rejected the null hypothesis. The effect size of the value differences can be considered medium for T_a conditions ($Tar^2 = 0.034$) and small for the T_g conditions ($T_g r^2 = 0.0054$). The ANOVA test for the RH conditions failed to reject the null hypothesis (RH DF = 1082; RH F-value = 1.46; $RH_p = 0.232$).

The Bonferroni (Dunn) test found that in terms of the T_a conditions three groupings formed in the data analysis (Table 45). As a result, while the indoor environment of the RTG performed thermally differently to the immediate outdoor environment, there are also two distinct thermal zones in the RTG itself. This revealed a thermal environment that dramatically increases the thermal amplitudes, as well as highlights that the northern zone of the RTG experiences consistently higher temperatures during the daily thermal peaks (Figure 85). In terms of the RH and T_g conditions there were no distinct groupings between the parameters, confirming that the variations between the RTG and outdoor conditions on the roof are negligible.

Table 45: Bon grouping for the three parameters measured in the winter Ta, RH, and Tg readings – SB farm.

T_a – Bon Grouping				**RH – Bon Grouping**				**T_g – Bon Grouping**			
	Mean	**N**	**LOC**		**Mean**	**N**	**LOC**		**Mean**	**N**	**LOC**
A	16.9014	361	North	A	31.2524	361	South	A	16.9939	361	North
				A				A			
B	15.3540	361	South	A	31.1861	361	Open	A	15.8751	361	South
				A				A			
C	14.3468	361	Open	A	29.7612	361	North	A	15.8684	361	Open
**Means with the same letter are not significantly different.*											
Abbreviations:				N – Number of observations LOC– Location							

The findings of the summer data analysis, as per the winter data, were congruent. The descriptive statistics for the ambient temperatures (T_a) revealed the northern ($T_{a\ mean}$ = 23.36°C; $T_{a\ max}$ = 39.10°C) and southern ($T_{a\ mean}$ = 23.77°C; $T_{a\ max}$ = 39.30°C) locations have similar mean and maximum T_a temperatures (Table 46). This was relatively higher than the Open T_a conditions ($T_{a\ mean}$ = 21.24°C; Ta_{max} = 34.60°C). As per the RH conditions, small variations between the three locations were documented, while the T_g conditions also documented limited significant variances. The mean indoor T_g conditions, north ($T_{g\ mean}$ = 24.40°C) and south ($T_{g\ mean}$ = 25.09°C), were slightly warmer than the open location ($T_{g\ mean}$ = 23.83°C). Concurrently, the open location experienced the highest T_g conditions ($T_{g\ max}$ = 52.20°C).

Table 46: Descriptive statistics of the Summer Ta, RH, and Tg readings - SB farm.

	Location	**N Obs**	**Mean**	**Std Dev**	**Median**	**Minimum**	**Maximum**
Ambient Temperature (°C)	North	289	23.36	6.48	21.00	15.70	39.10
	South	289	23.77	7.34	20.70	15.50	39.30
	Open	289	21.24	5.71	19.60	14.30	34.60
Relative Humidity (%)	North	289	63.66	19.15	65.30	24.70	91.10
	South	289	63.02	21.02	67.70	21.30	92.30
	Open	289	65.94	22.66	68.30	20.60	98.30
Globe Temperature (°C)	North	289	24.40	7.92	21.30	15.70	46.40
	South	289	25.09	9.19	20.80	15.00	47.90
	Open	289	23.83	9.75	19.40	13.50	52.20
Abbreviations:	N Obs – Number of observations Std Dev – Standard Deviation						

The visual display analysis of the T_a conditions showed that the indoor and outdoor T_a temperatures were highly correlated, but the T_a measurements for north and south were often slightly higher (Figure 87). Similar to the other sites the RTG was much warmer during the peak daily temperatures. In terms of the T_g conditions the open location consistently experienced the lowest temperatures during the coolest and the hottest periods of the day (Figure 88). Finally, the open location experienced the highest daily T_g amplitude.

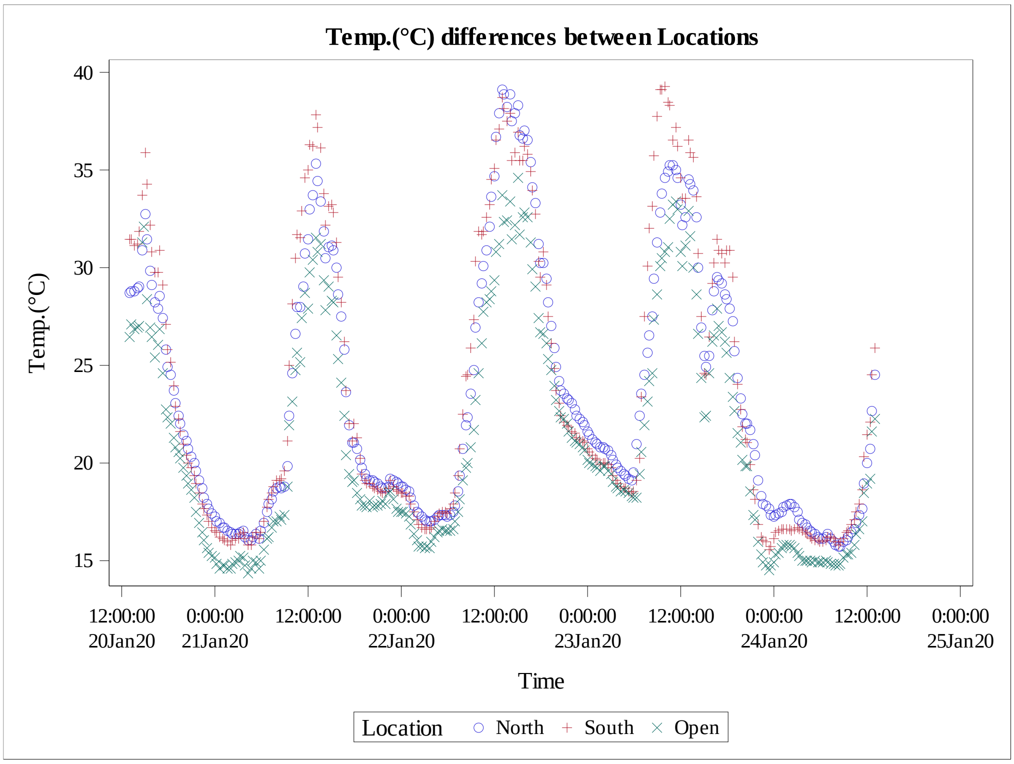

Figure 87: Summer Ambient temperature (Ta) differences between locations - SB farm.

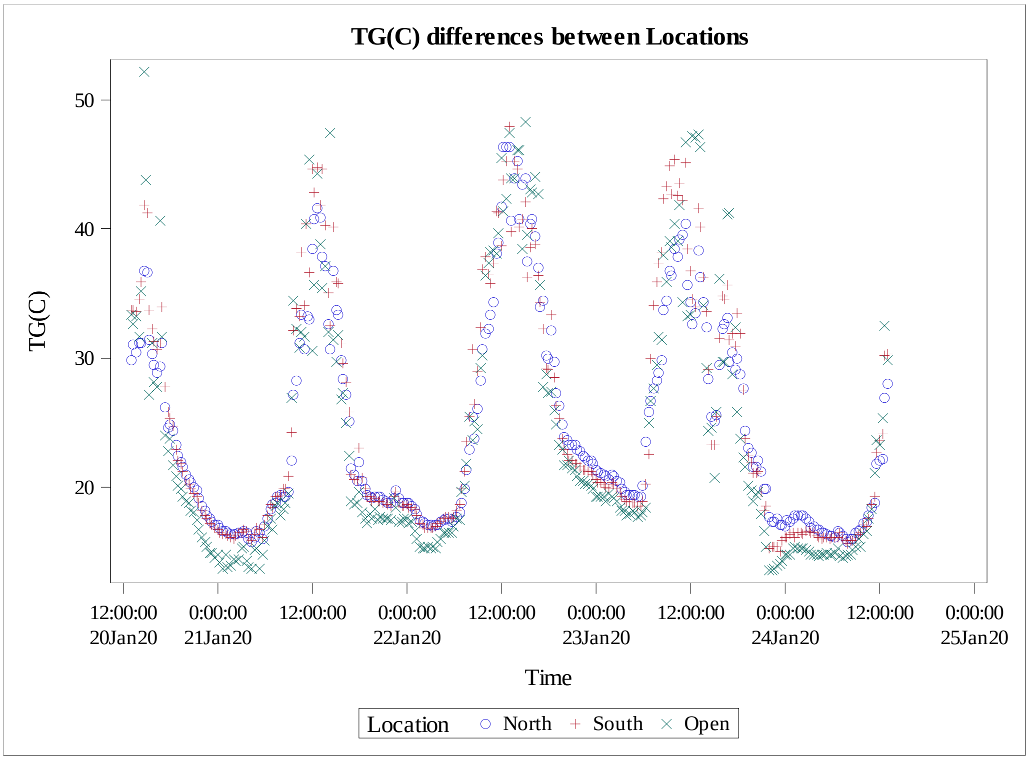

Figure 88: Summer Globe Temperature (Tg) differences between locations - SB farm.

The ANOVA test was performed for the three parameters. The T_a data confirm that there was an ambient temperature variation between the locations (T_a DF = 866; T_a F-value = 12.41; T_{ap} < 0.0001). The effect size of this variation is small ($T_a r^2$ = 0.0279), and therefore smaller than the T_a variations documented in the winter period. In terms of the other two parameters, the RH (RH DF = 866; RH F-value = 1.55; RH_p = 0.2125) and T_g (T_g DF = 866; T_g F-value 1.44; T_{gp} = 0.2379) conditions failed to reject the null hypothesis. Confirming that there was no significant statistical difference between various locations in terms of the RH and T_g conditions.

Furthermore, the Bonferroni (Dunn) test only identified distinct groups forming in terms of the T_a conditions (Table 47). The southern and northern locations correlated closely, while the open location was defined as a separate group (Table 47). Contrary to the winter data, the RTG had a more homogenous indoor temperature.

Table 47: Bon grouping for the three parameters measured in the summer period - SB farm.

T_a – Bon Grouping				**RH – Bon Grouping**				**T_g – Bon Grouping**			
	Mean	**N**	**LOC**		**Mean**	**N**	**LOC**		**Mean**	**N**	**LOC**
A	23.7657	289	South	A	65.944	289	Open	A	25.0941	289	South
A				A				A			
A	23.3592	289	North	A	63.662	289	North	A	24.3962	289	North
				A				A			
B	21.2398	289	Open	A	63.016	289	South	A	23.8280	289	Open
**Means with the same letter are not significantly different.*											
Abbreviations:			N – Number of observations LOC– Location								

The data from the T_a measurements of the SB farm show that the RTG consistently adjusted the indoor T_a conditions. This was more pronounced in the winter season than in the summer season. Furthermore, the bulk of the temperature variations occurred during the peak daily temperatures while at lower temperatures the variations were negligible. In terms of the other two parameters, RH and T_g, no statistically significant variations were documented. On the other hand, the visual analysis of the T_g findings shows that the outdoor conditions experienced the highest thermal fluctuations and were often the coolest at night, yet the magnitude of these differences was negligible.

3. Discussion of findings

The analysis reveals that the four RTGs located in Johannesburg that share structural and material characteristics (Table 29), vary in their overall ability to modulate their indoor environments. Three of the four sites consistently had two parameters that reflect no statistical variation between the indoor and outdoor conditions. Only the DHM farm had statistically significant variations for all the parameters, unfortunately only data for the winter season were available. Furthermore, the NM farm only displayed RH variations to a limited degree. Overall, limited consistent patterns of microclimatic modulation were documented in all the farms; in cases where modulation was measured the effect sizes are often small. The AGY farm is constructed differently from the other test sites by only using a 40% HDPE shade netting (Table 29). The AGY farm exhibited some statistical variation for all the parameters, except for the RH parameter in the summer season.

a) General ambient temperature, globe temperature and relative humidity conditions.

In terms of T_a conditions, all the farms revealed statistically different T_a conditions between the three locations in the winter period; yet the NM and MC farms did not demonstrate such differences in the summer periods. The farms that revealed the highest T_a differences were the DHM and SB farms; in both instances the effect size of the T_a variations is medium. The visual analysis revealed that all the farms followed similar patterns whereby large T_a variations were recorded during the hottest time of the day, while during the cooler periods (typically just before sunrise) the indoor and outdoor T_a conditions correlated. Essentially, the RTG structures consistently exacerbate the higher temperature conditions experienced on the roofs and fail to retain any thermal energy during cooler periods.

The T_g conditions were more inconsistent with 55% (n = 5 of 9) of the test periods revealing no statistical differences between the T_g conditions at the various locations. In contrast, the AGY farm showed statistically significant T_g variations in both phases resulting in lower T_g conditions in the indoor environment. However, the effect size of the variations is always small. In terms of the visual analysis the open location of the AGY and SB farms often documented much higher maximum and slightly lower minimum T_g conditions. This points towards the outdoor spaces being more exposed and the building structure itself experiencing much higher T_g fluctuations in the open conditions.

As for the RH parameters anomalous conditions were documented. In the MC farm the RH was always much higher within the farm. This contrasts with the other farms where the variations in relative humidity were either statistically negligible (44% of the cases) or the effect size of the variations is small. As a result, the MC farm performs differently from all the other test sites.

As stated before, distinct microclimatic variations rarely occur, yet the thermal deviations reveal less homogenous indoor environments. In cases where variations were documented, these differences often occured between the northern and southern zones of the RTGs (69% of the documented statistically significant cases). This points to diverse microclimatic conditions within the RTGs and limited control to achieve more homogenous indoor environments.

b) Limited climatic control

The analysis revealed that the RTG structures provide limited climatic control or thermal amelioration. The farmers often expressed this during discussions regarding their success in managing profitable farms. Many of the farmers mentioned season-related inefficiencies regarding their produce output and often experience climatic extremes that adversely affect their crops. To optimise the growing conditions one of the farmers installed a series of fans, used ice blocks to cool the nutrient mix in the summer and electric heaters to heat the mix in the winter (Figure 89). These strategies had limited success as the analysis noted that the specific RTG still underwent extensive thermal fluctuations. This corroborates findings from Thipe et al. (2017) that employing greenhouses without active climate control measures provide limited benefits in hot South African conditions[4].

Figure 89: Measures taken to improve the indoor environment. Photos taken at Stanop building and Minerals Council farms.

c) Bioclimatic design, choice of technology and material-use

The lack of climatic control can be attributed to the design of the greenhouses, construction material choices, and the quality of the workmanship. The fact that the greenhouses experience significant overheating at noon, points to high levels of solar gain captured in the RTGs. While the solar gain is critical to stimulate photosynthesis and evapotranspiration for nutrient uptake, these higher thermal conditions are not controlled nor retained to optimise growing conditions. On the other hand, the dramatic loss of indoor thermal energy can be

[4] Note that Thipe only assessed the performance of naturally (passive) ventilated greenhouses in typical industrial farming conditions and not its application as rooftop greenhouses.

attributed to the choice of the RTG envelope and the high levels of infiltration (Figure 90). This demonstrates the need for the improved bioclimatic design of the RTGs to modulate and control the thermal gain during the day as well as improving the insulation capacity to provide thermal benefits during colder periods. While these greenhouse structures are often used in soil-based farms and many urban farmers noted the benefit of using greenhouses, these structures must be optimised for smaller urban conditions that experience both extreme climatic conditions and require highly efficient produce outputs.

Figure 90: Envelope construction and finish. Photo taken at Stanop Building farm.

d) Choice of site and the impact of immediate context.

While the study revealed a general lack of microclimatic control, a few instances of significant differences were documented. As the farms all employ the same construction system and are generally similar in volumetric scale (except for the Tshwane example), it can be assumed that the analysis must have consistent findings. Interestingly, all four farms manifested microclimatic differences.

In three of the Johannesburg cases, dramatic differences in performance were documented, with the only variation between the three cases being the surrounding context. Beside small variations in RH conditions, the NM farm documented no statistically significant differences. This farm is essentially surrounded by built structures on the northern, western and eastern sides, and receives significant levels of overshadowing and wind protection (Figure 91).

In contrast, the SB farm is much more exposed. It is on the highest building in the surrounding area and experiences no overshadowing or wind protection. In this example there are differences in the T_a conditions, oftentimes resulting in increases of the already higher temperatures experienced on the roof (Figure 91).

Finally, the MC Farm's results reveal high RH conditions inside the RTG. These results differ significantly from the other sites. While the cause of the higher RH can only be postulated, some construction and contextual differences were noted. The RTG structure covers the whole balcony that it occupies, the balcony has a masonry upstand that is incorporated with the RTG structure and the RTG is protected from the western sunlight by a structure directly adjacent to it (Figure 91). As a result, the RTG structure is less open to wind flow and therefore has lower ventilation or infiltration rates; the envelope also seals better retaining moisture within. Both of these factors can result in higher RH conditions (Peet 1999). Furthermore, this RTG only has one walkway in the middle and is therefore more densely planted with lemon balm (a cascading herb with high leaf area coverage) (Table 29). Higher levels of vegetation-to-floor-area ratios can result in higher transpiration rates, further increasing the humidity (Peet 1999).

Figure 91: Images of contextual surroundings (left: MC farm; centre: SB farm; right: NM farm). Source: Aerial photograph sourced from Google Earth, accessed on 12 March, 2020 (Image on left); Author, 2019 (Image centre and right).

As a result, the findings emphasised the importance of site choice when limited microclimatic control strategies are being employed. In the case of the NM farm, the context and outdoor microclimate essentially control the indoor growing environment. On the other hand, in the highly exposed SB farm, we noted that the temperature variations are driven by the RTG structure and often at problematic periods – increasing the exposure of the already adversely affected produce. Only in the case of the MC Farm did the high crop coverage, lower temperatures and improved envelope construction (due to the existing structure) result in higher RH conditions that are favourable when growing produce using nutrient film technique (NFT) hydroponic systems.

4. Conclusion

This chapter addresses part of the third objective of the study, by documenting the thermal performance of a number of building-integrated agriculture (BIA) farms in Johannesburg and Tshwane. The choice of BIA farm type was passively controlled non-integrated RTGs, as the prevalent form used in South Africa. The study documented the T_a, RH and T_g variations at three locations in the farms.

The study documented limited control or improvement of the microclimate. This can be attributed to the design of RTGs, material choice of the envelope, quality of workmanship, as well as the site conditions themselves. These conditions have resulted in many farmers experiencing setbacks and varying quantities of produce output. Oftentimes farmers have expressed concern and difficulty in understanding the performance of the respective RTGs and the resultant produce output. This was also evident in the fact that some farmers started to develop their own strategies to improve growing conditions.

More data on how these RTGs perform in the South African urban context will assist farmers with the choice and application of RTG technologies, as well as develop measures to improve the indoor environment. This added understanding of the RTGs' performance can assist in designing improved RTGs that are bio-climatically appropriate to the context to optimise growing conditions. By modulating the range and nature of insolation, excessive midday thermal conditions can be controlled, while enhanced insulation properties can improve the indoor thermal environment during cooler periods at night.

The data collected during this study were used to inform the second part of the research objective, which aimed to assess the capacity of BIA farms as retrofitting strategy to limit the thermal exposure of the built environment to excessive climate change-driven heat increases. The findings from the research objective are discussed in Chapter 8.