Are the baseline control spaces at the BIFoR Free Air Carbon Enrichment experiment being polluted?

By

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Abstract

The Free Air Carbon Enrichment (FACE) experiments such as the one at the Birmingham Institute of Forest research (BIFoR), have emerged as a crucial tool for assessing the potential impacts of environmental increases in carbon dioxide (CO_2) concentrations on forests/woodlands of the future. Underpinning the BIFoR enrichment experiment there are two distinct levels of ambient control: the ambient blower spaces (ones with towers, pipework, and blowers) and the ambient undisturbed spaces (no infrastructure). By comparing the CO_2 concentrations together with the plant growth responses across, enhanced, blower, and undisturbed spaces, an improved understanding of future temperate woodland ecosystems can be predicted.

A critical aspect of the FACE methodology lies in its controlled approach, separating enhanced, blower, and undisturbed spaces. While previous studies have concentrated on the enhanced and blower spaces, this research focuses on the undisturbed spaces. A measurement system was designed and implemented within the three undisturbed spaces at BIFoR and used to examine – for the first time – the potential migration of the treatment CO_2 from the enhanced spaces into the undisturbed spaces. In addition, the data from the new system can be used to ascertain whether the ambient blowers are mixing the respired CO_2, lowering the measured ambient CO_2 concentration and therefore the enhanced spaces setpoint.

This study examined more than one million CO_2 concentrations measured within the undisturbed spaces at the BIFoR, FACE experiment, during the spring, summer of 2022. The results provide evidence that the undisturbed spaces are largely unaffected by CO_2 from the enhanced areas. For technical reasons summarised in this thesis, it was not possible to come to a firm conclusion about the effect of the blowers in the ambient spaces; this remains a question for further research. Overall, the study's outcomes reinforce the robustness of the

design of the FACE experiments. The data provides an important baseline, supporting and underpinning other experiments taking place at BIFoR FACE.

CONTENTS

1. INTRODUCTION

1.1. Background

Scientists, agree that the global mean atmospheric carbon dioxide (CO_2) concentration has risen significantly since the start of the industrial revolution, now almost 50% greater than the average of 278 parts per million (ppm) for the years 1750 to 1800 (Betts, 2021; Meehl et al., 2006; Szulejko et al., 2017), and is likely to rise even further.

The Birmingham Institute for Forest Research (BIFoR), Free Air Carbon Enrichment (FACE) experiment, was devised to investigate the effect an increased atmospheric CO_2 concentration could have on an established mature woodland (Norby and Luo, 2004). The predictions adopted at the start of the BIFoR FACE experiment were that the atmospheric CO_2 concentration could be as high as 550ppm by the year 2050 (Marcel et al., 2012; Wang et al., 2013). The experiment is enriching the CO_2 concentration, within defined spaces, inside a typical deciduous woodland called Mill Haft. The experimental design and the infrastructure are described in (Hart et al., 2020). The enhanced research spaces of the woodland are currently being exposed to extra CO_2 to a concentration of 150ppm above the measured ambient level. The average CO_2 concentration measured at Mauna Loa observatory for the year 2022 was 417ppm (NOAA, 2023), setting the BIFoR CO_2 concentration setpoint nominally to 567ppm, but it is continuously adjusted being calculated from the BIFoR measured ambient CO_2 concentration.

The Mill Haft woodland has nine experimental research spaces, each space is approximately 30 meters in diameter and 24 meters tall, containing a volume of over 21000 cubic meters. There are data loggers installed in each of the research spaces that record, soil temperature and soil moisture (at the surface and at incremental depths up to 1 metre), the rainfall through the canopy, and tree transient sap flow. The Mill Haft woodland is a small space encompassing a total area of approximately 19ha (hectares), of which about 8ha are designated for research, see figure 1 for a general arrangement of the site.

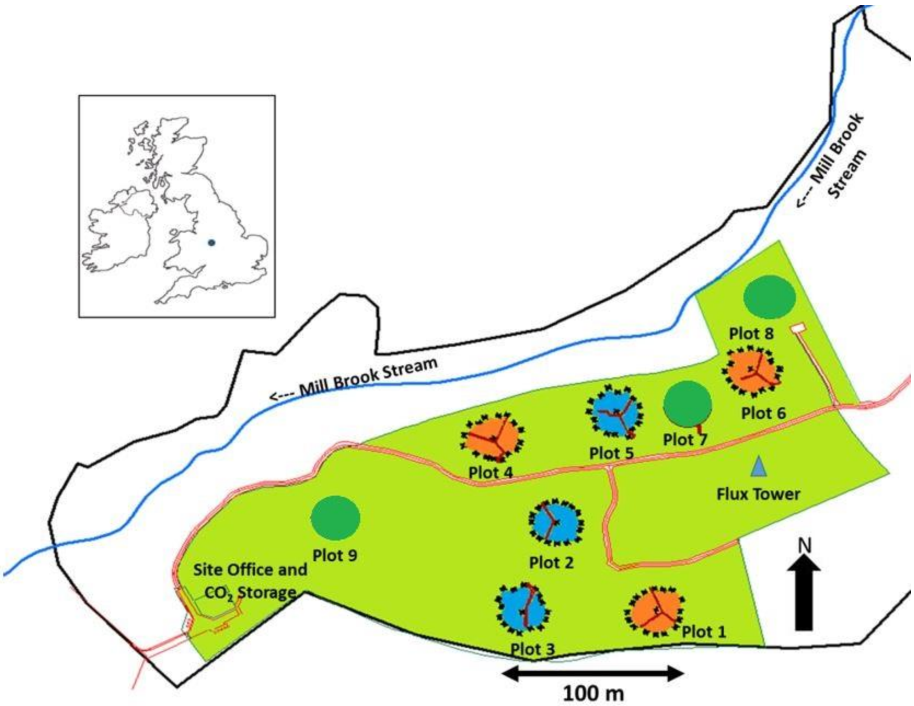

Figure 1: General arrangement of Mill Haft research site. The map shows the general layout of each of the research spaces (shown as Plots in this map). The area shown light green is the extent of the experimental site. (Hart et al., 2020). The spaces are highlighted as follows; the eCO_2 spaces shown orange, the bCO_2 spaces shown blue and uCO_2 spaces shown dark green.

The nine research spaces are split into three treatment categories:

1) CO_2 enhanced air (eCO_2 spaces): Three spaces are treated with an extra 150ppm (parts per million) of CO_2 above the measured ambient CO_2 concentration. Situated outside each space is an air blower, distribution pipework, and 32 vertical dispersal pipes suspended from 16 lattice towers.
2) Ambient blower research spaces (bCO_2 spaces): Three spaces are a control group, they have the same blowers (the same air flow), the same structures, pipework, and CO_2 monitoring systems as the enhanced research spaces, but no extra CO_2 is added.
3) Ambient undisturbed research spaces (uCO_2 spaces): Three spaces are a further control group; these spaces have no blowers or structures. They are used as a baseline

to show how the woodland changes with the minimum of interference. Without the disturbance caused by the construction, or operation of the FACE infrastructure, and the extra air flow from the blowers found in the eCO_2 and bCO_2 spaces.

The three eCO_2 spaces are each equipped with a CO_2 delivery system. Around the edge of each research space are sixteen 25m tall metal lattice towers, each supporting two black distribution vertical vent pipes (VVP) (32 pipes for each space), an air blower, ducting and an additional central monitoring tower. The towers were constructed in a mature woodland and were arranged to minimise disturbance to the trees, so are not a perfect circle. Figure 2 shows a schematic diagram of an enriched space, showing just two of the VVPs the lattice towers and the other thirty VVPs are omitted for clarity.

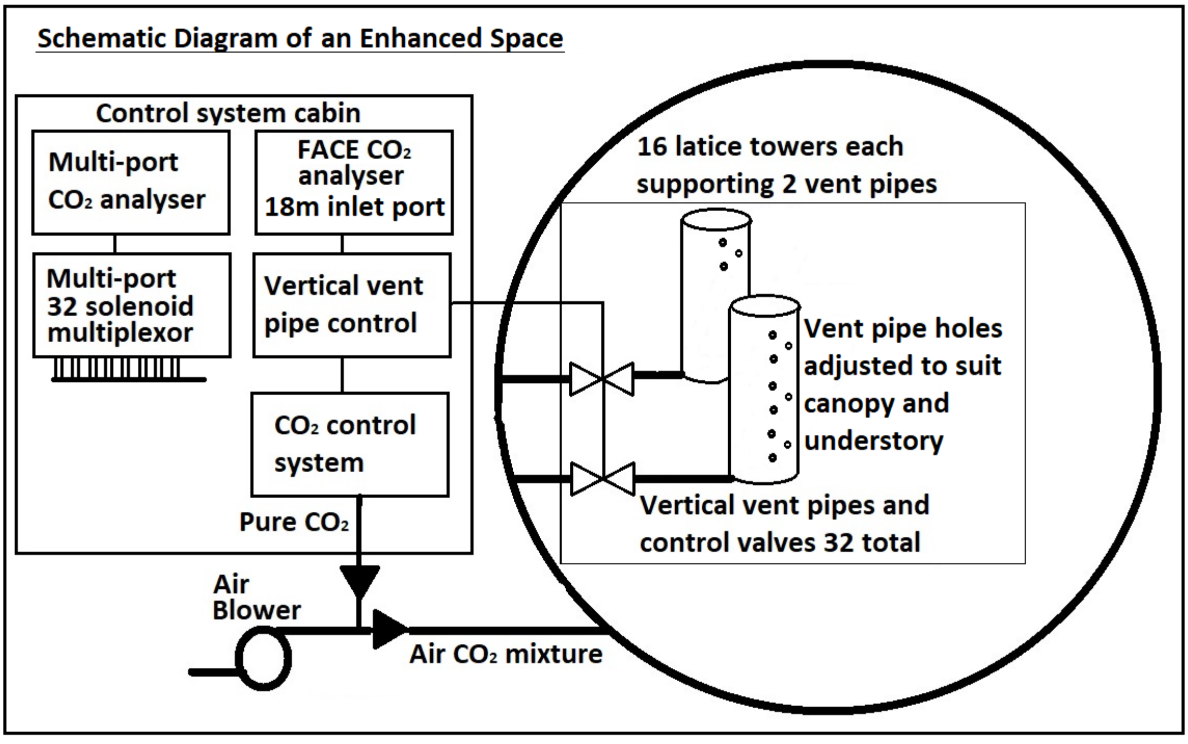

Figure 2: A schematic diagram of an enriched research space. Showing the main control elements and just two of the 32 vertical vent pipes. The 16 support towers and 32 multi-port inlet ports omitted for clarity.

There are two CO_2 monitoring systems, one continuously samples and records the CO_2 concentration at 18 meters high, in the centre of the research space. The second is connected to a multiplexor to record the actual CO_2 concentration sampled from thirty-two points spread throughout the research space (known as the Multi-Port or MP system). The inlet ports to the MP system are arranged as follows; there are 8 ports vertically on the central tower from 0.2m above ground to the top of the tower at approximately 24m-26m high depending on tower height, the other 24 ports are arranged on the cardinal points of the compass at 2m, 10m, 24m, height and at 6m and 12m from the central tower. This arrangement allows the spatial dispersion of the CO_2 concentration to be monitored throughout the entire eCO_2 space.

The three bCO_2 spaces, are replicas of the eCO_2 spaces having the same arrangement of towers, pipes, blowers, and the two CO_2 monitoring systems. The data from the MP system in the bCO_2 spaces is examined regularly to identify if there is pollution from the eCO_2 spaces reaching the bCO_2 spaces. The monitoring system also shows the spatial dispersion of the naturally occurring respired CO_2 within the bCO_2 spaces.

The three uCO_2 research spaces, have no blowers, no piping or towers and no CO_2 monitoring system.

The three sets of research spaces were carefully chosen to reflect a similar soil composition and species mix of pedunculate oak (*Quercus robur*), common hazel (*Corylus avellana*), and other self-set species, particularly sycamore maple (*Acer pseudoplatanus*) (Hart et al., 2020). The research spaces were designated, and the replicate trio compared as shown in table 1.

Table 1: Research space allocation and association for comparison, see figure 1 for the general arrangement of the research spaces.

	Enhanced space (eCO_2)	Blower space (bCO_2)	Undisturbed spaces (uCO_2)
Set	Treatment Extra CO_2 and Extra air	Treatment Extra air flow	Treatment None
1	1	3	9
2	4	2	7
3	6	5	8

1.2. Research Motivation

This project, the baseline control space monitoring project, investigated the background CO_2 concentration found in the natural woodland environment. The system recorded and continues to record the CO_2 concentration vertically at five different heights in the centre of the uCO_2 spaces, figure 3 shows the general positioning of the sample points. This data will provide a record of how the background atmospheric CO_2 concentration has changed over the duration of the BIFoR FACE experiment. This is the first time the CO_2 concentration in the uCO_2 spaces, has been continuously recorded at a woodland FACE site. Other FACE experiments research, has concentrated on the atmosphere within the bCO_2 and eCO_2 spaces only (Ainsworth and Long, 2021; Bazzaz and Williams, 1991; Kimball et al., 2021; Pepin and Körner, 2002; Pippen, 2007).

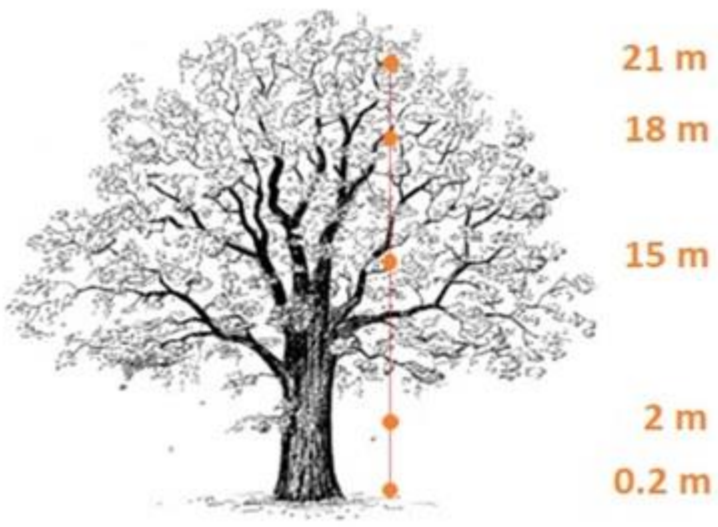

Figure 3: Air sampling points. The typical arrangement of the air sampling inlet ports suspended from a tree branch closest to the centre of the research space. Image adapted from (Mateusz, n.d.).

This research will provide a record of the uCO_2 spaces CO_2 concentration, data that can be used to underpin other experiments taking place at BIFoR FACE. Recording the ambient CO_2 concentration at different heights will quantify, if, when, how much, and at what height any pollution occurred.

In addition, this new data will be used to determine whether the actual CO_2 setpoint across the entire experiment is set correctly. The setpoint for the eCO_2 spaces is calculated by selecting the lowest measured CO_2 concentration of the three bCO_2 spaces, then adding the treatment value (an extra 150ppm for BIFoR FACE). It is possible that the bCO_2 space blowers are causing a disturbance and a mixing of the air and respired CO_2 within the bCO_2 spaces, thereby lowering the bCO_2 space CO_2 concentration and the eCO_2 setpoint. By comparing the actual CO_2 concentration recorded at the uCO_2 spaces, to the CO_2 concentration recorded at the bCO_2 spaces, it will be possible to evaluate the difference in CO_2 concentration between the uCO_2 and the bCO_2 spaces.

1.3. Research Aims

The aim of this research is to investigate the CO_2 concentration found in the uCO_2 spaces at BIFoR woodland and to establish an accurate local atmospheric ambient CO_2 concentration baseline. This record of the measured CO_2 concentration within the uCO_2 spaces will be a valuable dataset showing, how the natural woodland respiration has changed over the course of the experiment. The data will be examined to identify if there has been any pollution from the eCO_2 spaces. If pollution has occurred, the data will be analysed to understand the potential source and the amount of pollution. This will be an important record underpinning, all the BIFoR experiments.

1.4. Objectives

1. Design and install measurement stations in the three uCO_2 spaces.
2. Measure and record the ambient CO_2 concentration at the centre of the three uCO_2 spaces, at five vertical heights, at 0.2m, 2m, 15m, 18m and 20m.
3. Analyse the uCO_2 spaces CO_2 concentration records, to identify if any pollution has occurred.
4. If pollution has occurred, establish the source of the pollution.
5. Investigate the accumulated datasets, to assess the accuracy of the current bCO_2 ambient measurements and communicate to the BIFoR scientific community if there is a significant difference in the CO_2 concentration between the bCO_2 spaces and the uCO_2 spaces.

1.5. Outline Structure

Following this introductory Chapter 1, in which the background and the aims of this research have been presented, the thesis will continue as outlined below.

The literature review, Chapter 2, discusses the need for good empirical data to advance scientific understanding and support model development . This chapter investigates the challenges associated with the different approaches to free air Carbon Dioxide enrichment experiments. Highlighting the different levels of control required to provide robust experiments.

Chapter 3 introduces the research methods. It outlines the approach taken to record the ambient CO_2 levels at the different heights within the undisturbed research spaces, of woodland at BIFoR. The equipment developed as part of this research is introduced and the installation of that hardware at BIFoR is discussed. In addition, the limitations and possible improvements are discussed.

In Chapter 4 the findings of the research are reported, documenting the actual CO_2 found in the undisturbed research spaces and documenting the uncertainty in the data.

Chapter 5 reports on the conclusions that can be drawn from the findings discussed in chapter 4 and comments on the areas for future work.

The final sections of the thesis are the references and appendices. The appendixes contain detail design information. Appendix A contains the cabinet layout arrangement drawings. Appendix B contains a listing of the Python code, the code is available to download and to use from the repository at github.com.

https://github.com/NickBIFoR/uCO2Monitoring/blob/main/Ghost_MPReadW_D2.py.

2. LITERATURE REVIEW

2.1. Importance of Measuring CO_2

The amount of CO_2 in the atmosphere is one of the fundamental measurements used by environmental scientists as an indication of the health of the planet (Betts, 2021; Ciais and Sabine, 2014; Norby and Luo, 2004; Walters et al., 2011; Wang et al., 2013).

CO_2 is a greenhouse gas (GHG), the term used to describe any gas that absorbs solar radiation thereby increasing the temperature of the air in the atmosphere. CO_2 is not the only greenhouse gas, it makes up approximately 76% of all the GHG emitted due to human activity; the others are methane (CH_4) 16%, nitrous oxide (N_2O) 6% and fluorinated gases 2% (Greenhouse Effect 101, 2019).

A study investigating the global warming effect of different gases in the environment, found that the radiation wavelengths absorbed by CO_2 were responsible for 25% of the total greenhouse radiative heat forcing (trapping of radiation), even though CO_2 currently makes up only about 0.04% of the atmosphere. It was also found that at concentrations over 800ppm, the heat trapping function of CO_2 increases supra-logarithmically (Zhong and Haigh, 2013) (i.e. a non-linear way faster than a logarithmic function).

Water vapour in the atmosphere also acts as a GHG, more water vapour in the atmosphere will also increase the Earth's temperature. The volume of water vapour in the atmosphere is a function of the atmospheric temperature, therefore the warmer the atmosphere the more water vapour that can be supported. However, water vapour will condense into clouds in the upper atmosphere as the temperature drops and eventually fall as rain. The water vapour in the atmosphere has a low residence time eventually condensing and failing as rain. The water vapour does not build up year on year so is not considered to be a cause of global warming, but it is affected by global warming. In contrast the impact of anthropogenic production of

CO_2, CH_4 and N_2O, which are non-condensable at atmospheric temperature and pressure, and therefore are building up increasing concentrations (year on year), does affect global warming (ACS Chemistry for life, 2018).

2.1.1. Historical Atmospheric CO_2

In a recent study of microscopic fossilised shells found in ice cores (the Foraminifera Project), the atmospheric CO_2 concentration from the past 66 million years were recreated (see figure 4), back to the formation of the polar ice cap (Lee, 2021). This showed that 50 million years ago the climate was much warmer with CO_2 concentration in the region of 1500ppm. During the Ice Ages the CO_2 concentration reduced dramatically, eventually dropping below 300ppm. There followed a long period of stability for nearly 800,000 years where the global CO_2 concentration had been in an equilibrium, varying between 180 ppm to 278 ppm, until AD1870 the beginning of the industrial revolution in Europe. Since the start of the industrial revolution the concentration of CO_2 has risen by over 50%, with CO_2 levels now exceeding 417ppm (Betts, 2021).

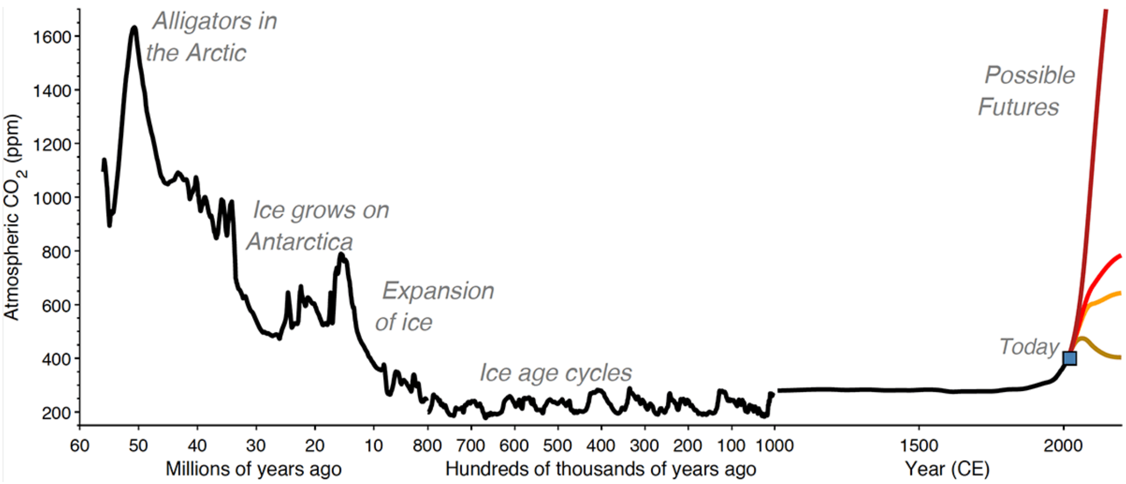

Figure 4: Polar ice fossil recreation of historical CO_2 concentrations. The graph shows how the CO_2 concentrations fell from over 1000ppm, to a long period of CO_2 equilibrium at around 250ppm. Then a sudden increase at the start of the industrial revolution. Also showing projected concentrations, using the worst and best case forecasts (Lee, 2021).

Long periods of atmospheric stability allowed a rich flora and fauna to evolve and to develop to give a broad biodiverse ecosystem.

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) observed that during the period 2011-2023, the global surface temperature was 1.1^{o}C above that recorded between 1750-1900 (Calvin et al., 2023). The report highlighted that while the GHG emissions had increased across most regions the emissions are not evenly distributed. Measuring the background CO_2 concentration at multiple sites across the world in differing ecosystems will allow a better understanding of how the whole biosphere is responding to the changing atmosphere (Balsamo et al., 2021; Norby and Luo, 2004).

2.1.2. Historical Atmospheric CO_2 Measurements

The longest running measurement of atmospheric CO_2 concentration, has been measured at Mauna Loa since 1958, by the National Oceanic Atmospheric Administration (NOAA, 2023). The Mauna Loa observatory is based on a volcano at a height of 3397 meters (11,135 feet) above sea level, on the island of Hawaii in the Pacific Ocean, at latitude 19.54 degrees North, longitude 155.58 degrees west. This site was chosen as the remote location and elevation allows the air sampled to be largely unaffected by vegetation or human activities (Keeling, 1977). Unfortunately, observations were suspended on 29 November 2022 after the Mauna Loa volcano erupted. Since December 2022, the NOAA CO_2 concentration measurements are being taken at the Maunakea Observatory approximately 21 miles North of Mauna Loa Observatory (NOAA, 2022). Figure 5, shows the atmospheric CO_2 and emissions since 1750, highlighting how rapidly the concentration has risen since 1870s.

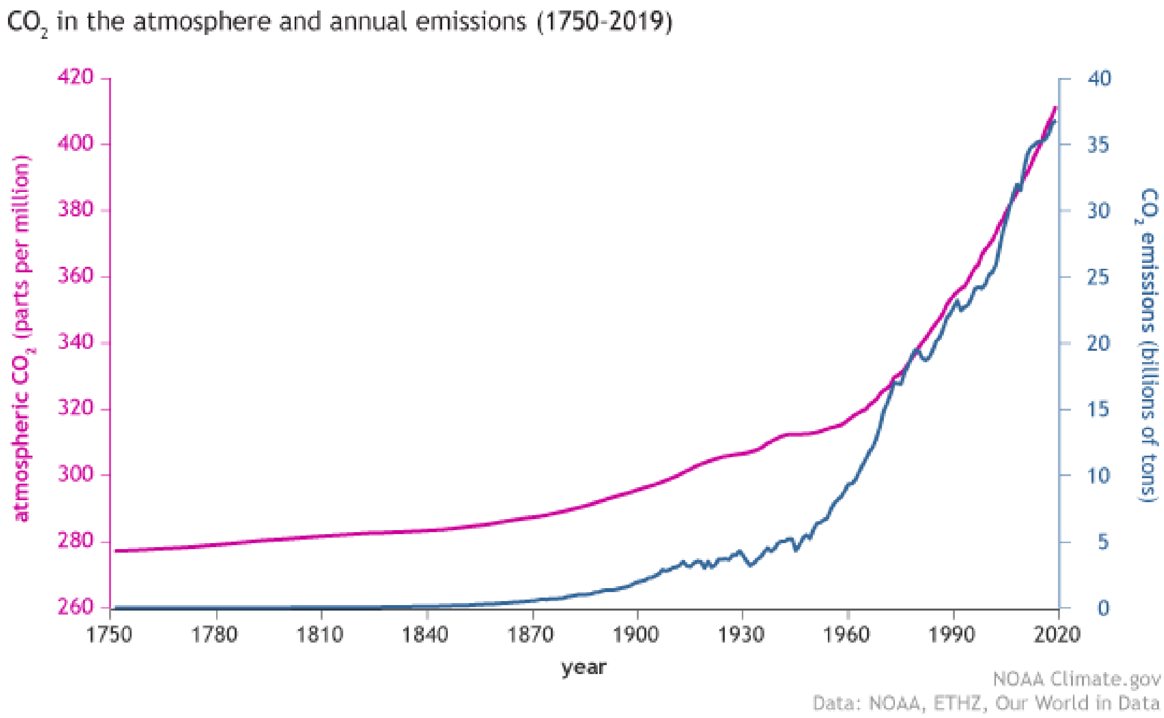

Figure 5: CO_2 concentration in the atmosphere and annual emissions (1750-2019) (U.S. D of C and NOAA, 2023)

Global industrialisation has a double impact on the environment, the widespread use of fossil fuels increasing the global CO_2 emissions and the change of land use reducing the carbon sink, leading to an overall increase in the global quantity of CO_2 in the atmosphere(Friedlingstein et al., 2022). Forests are an important carbon store, accounting for the largest carbon store on land; 'one-third of this is carbon is stored in biomass and two thirds of it in soil' (Wang and Huang, 2020).

2.1.3. The Current Annual CO_2 Trend

The Mauna Loa observatory has shown a steady increase in CO_2 concentration year on year, the black line in Figure 6. The red line in the chart shows the monthly average CO_2 level, this has an annual cycle. (NOAA, 2023).

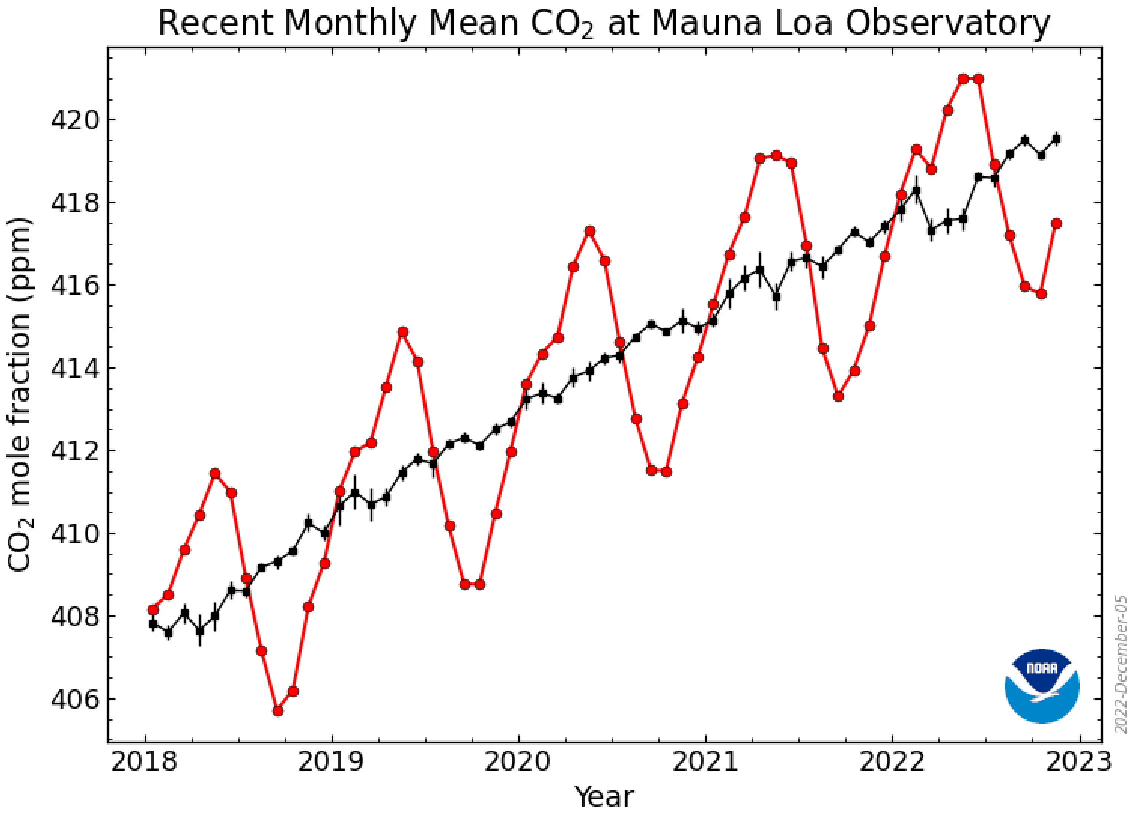

Figure 6: The CO_2 trend as measured at Mauna Loa over the last 5 years (NOAA, 2023). The red trace is the monthly average, the black line is the calculated yearly moving average after correction for seasonal cycles.

The CO_2 cycle is driven by a combination of green leaf photosynthesis and anthropogenic activity(König et al., 2023). During the warmer months in the Northern hemisphere, the green plants, mainly woodlands absorb CO_2, with a maximum CO_2 absorption, a minimum absolute atmospheric CO_2 concentration occurring in May. As explained by (Cleveland et al., 1983), the cycle is not driven solely by plant photosynthesis as the maximum absolute CO_2 concentration, occurs in October, this could be because the anthropogenic sources of CO_2 are higher in the darker cooler months when heating systems are emitting more CO_2.

Woodlands play a crucial role mitigating climate change through several mechanisms. Trees absorb CO_2 from the atmosphere during photosynthesis, storing the carbon in their biomass and releasing the Oxygen (O_2) into the atmosphere. Trees help to regulate the water cycle by absorbing and releasing water through their roots and leaves. Forests have a darker surface area when compared to grassland or bare soil, absorbing sunlight rather than reflecting it into the atmosphere. Forests provide a habitat for a diverse range of plants and animal species (Burton et al., 2018; Valdés et al., 2020).

2.1.4. CO_2 Predictions

There are many factors governing the amount of CO_2 in the global environment. The Centre for Climate Systems Research (CCSR), Columbia University, used several computer models to develop the Representative Concentration Pathway (RCP) model. This set out several scenarios, from a worst case RCP8.5, where global warming is increasing by 8.5 watts per square meter (Wm^2) to a best case RCP2.6 where the warming is 2.6 Wm^2. Under RCP8.5 CO_2 levels could reach 550 ppm by the year 2050 (Nazarenko et al., 2015). These RCP pathways have been fundamental in setting the climate change limits agreements at the United Nations Climate Change Conference, the Conference of Parties (COP), and the limits agreed in the Paris agreement (Balsamo et al., 2021). It is apparent that even using the best-case scenarios CO_2 concentrations are going to rise.

It is essential that we understand how the change in the Earth's atmosphere will influence nature and the numerous interactions within the natural biosphere. Looking at a single plant, or plant species, in a confined environment, then scaling that up to woodland landscape will not provide a good metric for how the various systems within the ecosystem interact (Hendrey, 1992a). Hence researchers have proposed a range of CO_2 enrichment experiments which have two main goals as explained by (Hendrey and Kimball, 1994) *"(1) to evaluate the effects of increasing CO_2 concentrations on plants and ecosystems; (2) to contribute to an evaluation of terrestrial plant feedback regulation of rate of change of CO_2 in the atmosphere.)"*.

2.2. Enriched CO_2 Environment Experimentation

There are four main types of enriched CO_2 experimental facilities: greenhouses, open topped chambers, screen-aided CO_2 control and free air carbon enrichment (FACE). There are advantages and disadvantages of each of these systems. There follows a brief discussion of each.

2.2.1. Greenhouses

Greenhouses have been used in numerous experiments to good effect. They are enclosed environments where young plants are exposed to prescribed environmental changes such as changes in light, heat, Ozone (O_3), or CO_2 separately or in combination. Greenhouse experiments are usually carried out on young, short, potted plants that have been grown from seed in an enclosed environment. Greenhouses are a useful environment, enabling the testing of a plant response to single environmental variable, in a transferable and reproducible environment. Attempting to do this in a field crop would be difficult, as field crops will be exposed to different conditions season to season (Ainsworth and Long, 2021). However, greenhouse plants will not have been exposed to other environmental factors such as wind, rain, frost, or other factors existing in the biosphere. Hence, it is important when investigating tree growth and health, that these environments are used along with other outdoor field experiments (Norby and Luo, 2004).

2.2.2. Open Topped Chambers

Open topped chambers (OTC) are tall chambers with an open top, they allow a tree to grow to maturity in the chamber, or for the chamber to be built around an existing tree, or small group of trees. The chamber environment can be closely controlled, allowing changes in temperature or gas composition, or both, but still allow the tree to experience other environmental factors, such as rain. Figure 7 shows an example OTC used in the amazon rainforest, to assess the effect of raising the CO_2 concentration on a small natural shrub-tree. However the open topped chambers do not allow the tree to experience the full force of the wind, leading to the so called chamber artifact as described by Hendry and Kimball (1994).

Figure 7: An example, open topped chamber at Amazon OTC experimental site. (Photo. The author)

2.2.3. Screen Aided CO_2 Control

Screen-Aided CO_2 control systems provide a middle ground between the open topped chambers and a full-sized FACE experiment. The paper (Leadley et al., 1997, p. 1) explains that poly carbonate screens were designed to create a screen around a research space of plants, figure 8. The screens were shorter than the crop and space was left beneath to allow animals and wind to circulate freely. It was reported that, the screen had little or no effect on the micro-climate, avoiding the heating experienced in open topped chambers. The screens used in this experiment were short and still only enclosed a relatively small research space ($1.27m^2$), scaling them up to a group of fully grown trees would be unfeasible, due to the large frames required to support the screens.

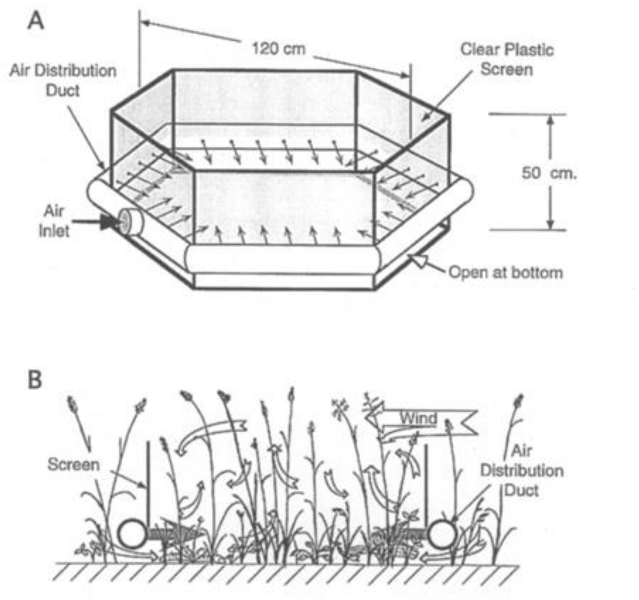

Figure 8: Screen Aided CO_2 Control. A) General arrangement of the screen. B) Notice the wind blowing under and over the screen creates a turbulence to promote mixing of CO_2 and air (Leadley et al., 1997).

2.2.4. Free Air Carbon Enrichment (FACE) Experiments

The Free Air Carbon Enrichment (FACE) experiments are designed to change the environment around a plant or group of plants in a research space of a field or woodland without any enclosures. Allowing the plants to be in as natural environment as possible, exposed to wind rain and temperature extremes, with the addition of CO_2. Any type of enclosure could have a modifying effect on the experiment, as Ainsworth and Long explain "Enclosures may amplify downregulation of photosynthesis and production, and may through environmental modification produce a 'chamber affect' that exceeds the effect of elevating CO_2."(Ainsworth and Long, 2005, p. 2). The FACE experiments are judged to provide a good understanding of how the entire ecosystem will respond to the increased CO_2 in the environment. However, there are several disadvantages of the FACE experiments; the space required for the enhanced spaces and the two levels of ambient controls (blower and undisturbed spaces), the size of the infrastructure towers and distribution pipe work, the initial cost to build the system, plus the running cost of purchasing the large volumes of the CO_2 required. The tall tree FACE technologies are discussed in the next section 2.3.

2.3. Tall Tree FACE Technology

Currently there are two main types of tall tree FACE experiments, the Brookhaven National Laboratory (BNL) designed system, where pure CO_2 is added to air blown by a blower, then distributed around the outside of the experimental area through large pipes, and the WebFACE experiments where pure CO_2 is delivered directly into the plant canopy through small bore pipes. The FACE technologies were developed initially to treat short annual crops, these have been developed into large scale systems for dosing tall trees. The following text discusses the tall tree FACE experiments only.

The BNL system requires large infrastructure, a CO_2 vaporising system, air blowers, extensive ductwork, and vent pipes, built around the outside of the experimental space. The upwind pipes are opened to emit the CO_2 enhanced air mixture, onto the wind to be carried into the experimental space (Hendrey and Kimball, 1994). The installation costs of these experiments are huge due to the large amount of infrastructure required and that the infrastructure is repeated into the bCO_2 spaces. Also, the ongoing running cost is large due to the cost of running the electrical blowers and the cost of procuring large quantities of CO_2. Another major drawback of this design of FACE is the disruption caused during the installation of the large towers and pipes into an existing ecosystem. This impact is immediate and can take some time for the ecosystem to recover. It is imperative that the construction contractors and researchers, are aware of the ecological impact and take every measure to minimise this impact on the existing ecosystem.

For each enhanced space, two control spaces are recommended; an ambient blower space where the infrastructure is repeated from the eCO_2 spaces (including blowers, pipes distributing air only); and an ambient undisturbed space where no infrastructure is built. Early BNL FACE experiments did not include undisturbed spaces. It can be difficult to identify three replica spaces with a similar mix of flora, soil types, and sufficient distance between spaces to avoid contamination. But without the uCO_2 spaces it is not possible to truly understand the impact on the ecosystem of the initial construction, of the extra CO_2/air mixture in the eCO_2 space, and the extra air blown into the bCO_2 spaces.

The second type of FACE experiment, WebFACE sends pressurised pure CO_2 through a network of small pipes wound around the plant of interest. This technology has been dubbed WebFACE due to the similarity to a spider’s web. The small pipes have precise laser drilled holes of 0.5mm diameter, approximately 25,000 per tree crown, the holes are designed to produce a jet of CO_2 to promote mixing of the CO_2 with the local ambient air. The infrastructure involved in this is much smaller and causes much less disturbance to the ecosystem, the demand for CO_2 is less and with reduced overspill (Pepin and Körner, 2002).

Another advantage is that there is no need for any infrastructure in the ambient spaces, thereby only requiring one level of control, reducing the space required, less initial cost and less disturbance. However, the major drawbacks are that there can be a wide variation in the concentration of CO_2 reaching the leaves of the tree under examination, plus the lower branches and the understory are not dosed. A question resulting from this type of experiment is, if the lower branches and the understory are not treated with CO_2, can this be considered as a whole ecosystem test environment?

2.4. The BNL FACE Experiments

FACE experiments have been taking place since the 1970s (Harper and Baker, 1973), initially to study the CO_2 fertilisation effect, on a target commercially grown crop. The FACE technology used at BIFoR was developed by BNL in the late 1980's, with the first large scale experiment sited at Maricopa, Arizona, in 1989 (Hendrey, 1992b). Figure 9 shows the Maricopa site, the crop being fertilised was short, utilising short plastic welded self-supporting vertical vent pipes.

Figure 9: Maricopa, Arizona. Agri-FACE research focused on the fertilisation of short commercially grown agricultural crops (*Image by Bruce Kimball / USDA)*. Note the extensive flat site, making replication and distancing easy.

The first generation of BNL FACE experiments were designed to treat annual, commercially crops with CO_2. The crops studied included cotton (*Gossypium*), wheat

(*Triticum aestivum*), sorghum (*Sorghum bicolor*), maize (*Zea mays*) and soybean (*Glycine max*). These experiments were part of a United Sates Department of Agriculture (USDA), initiative to predict the fertilisation effect of the increased CO_2 in atmosphere and the resultant crop production (Hendrey and Kimball, 1994). The FACE fertilisation experiments were expanded to focus on tree growth. Dickson et al explained. "*To be affective, FACE experiments must continue for enough time to clearly separate response to treatment from response to seasonal environmental changes. Experiments should continue for two to three life cycles of annual plants, 3 to 5 years for perennial grasslands, and 10 to 15 years or longer for forest stands*" (Dickson et al., 2001).

2.4.1. Duke FACE

The prototype FACE tree system was installed at Duke FACE, a Loblolly pine (*Pinus taeda*) plantation 1994 (Norby and Zak, 2011). Where this experimental setup differed from field crop experiments, was the addition of tower structures to support the vertical vent pipes. The vent pipes could be raised up as the trees grew, as shown in figure 10 (Schlesinger et al., 2006).

Figure 10: Duke FACE. Tree fertilisation experiment, showing adjustable vent pipes and supporting towers (Pippen, 2007).

After the success of the first eCO_2 area, the Duke FACE experiment was extended in 1996 to include three additional enhanced spaces, four enhanced CO_2 total with three ambient spaces (ambient spaces at Duke, included blowers and distribution pipes, referred to as blower spaces throughout this document) (Schlesinger et al., 2006). Duke FACE also designated one space as an undisturbed space, there was no monitoring of the CO_2 concentration, this space was periodically sampled for soil phosphate and nitrogen concentrations (Jackson et al., 2009).

2.4.2. Aspen FACE

The Aspen FACE experiment began in 1998, focusing on the responses of aspen (*Populus tremuloides Michx*), paper birch (*Betula papyrifera Marsh*), and sugar maple (Acer saccharum Marsh). Aspen FACE while looking at the fertilisation effect of CO_2, also examined the pollution effect of Ozone (O_3), the gases were dosed, separately and together (Gustafson et al., 2020). The planation was situated in previously fertilised arable farmland. Aspen FACE required large separation between spaces to avoid the cross contamination of the O_3 which is extremely toxic to humans and plants. Figure 11 shows an aerial view of the site, note the wide separation of the experimental research spaces.

Figure 11: Photograph showing the Aspen FACE site. The site was arranged with a large separation between different research spaces to avoid the possibility of cross contamination of the experiment (Gustafson et al., 2020).

2.4.3. Oak Ridge FACE

Oak Ridge National Laboratory (ORNL) was situated in a closed canopy high sweetgum (*Liquidambar styraciflua*) plantation, the spaces were 25-meter diameter and 12-meters tall. Situated at the Oak Ridge National Laboratory in Tennessee, USA, it began CO_2 treatment in 1997 (Norby et al., 2006). Figure 12 gives an overhead view of ORNL FACE experiment showing the general arrangement of the site, note the regular spacing of the trees indicative of a plantation. The towers were equipped with winches to pull the vent pipes up to the canopy height and could be adjusted as the trees grew.

Figure 12: Photograph of the Oak Ridge FACE experiment. Overhead view of the site showing the eCO_2 and the bCO_2 research spaces, note the regular spacing indicative of a plantation (Ainsworth and Long, 2021).

2.5. Second Generation Tree FACE, the Eco-System Experiments

The results from the fertilisation experiments concluded that there was an element of uncertainty, that while the fertilisation experiments provided a deeper understanding of how a forest responded to increased CO_2, there was an uncertainty in the allocation of the carbon budget (Norby et al., 2016a). Recommending that future experiments should study the entire ecosystem, to truly understand the carbon budgets and carbon allocation (De Kauwe et al., 2014).

A new generation of FACE experiments was required, ones that would need to be better integrated into the existing ecosystem and would need to study different biomes. The new sites would need to look at wide ranging science questions, looking at the woodland interactions with temperature, water stress, phosphorus and nitrogen depletion (Norby et al., 2016b).

2.5.1. EucFACE Ecosystem Experiment

The Eucalyptus FACE (EucFACE) experiment was the first of the second generation, ecosystem wide CO_2 enrichment experiments. It is based in a mature evergreen Eucalyptus (*Eucalyptus tereticornis*) woodland in western Sydney Australia, the existing woodland has been unmanaged for over 90 years (Jiang et al., 2019). There are three eCO_2 and three bCO_2 spaces, but no measurements are taking place in the undisturbed spaces. EucFACE has a large hard plastic pipe distribution system, with a man-lifting crane situated outside the experimental area, as shown in figure 13. The results from EucFACE indicated that the carbon uptake of the woodland had been over estimated and that the lack of phosphorus in the soil had down regulated the CO_2 uptake (Crous et al., 2019; Jiang et al., 2019), reinforcing the need for further FACE experiments in differing ecosystems.

Figure 13: The EucFACE experiment. An aerial view of the site, showing the 6 experimental rings in white with the associated cranes shown green. This picture highlights the space required for such large-scale experiments. (Photograph D.Ellsworth).

2.5.2. BIFoR FACE Experiment

BIFoR has been designed to utilise and improve upon the successful aspects of the previous projects, expanding to fill some of the knowledge gaps (Hart et al., 2020). The performance of the eCO_2 spaces and bCO_2 spaces can only be confirmed, by comparison of the entire ecosystem found in each of the spaces, referenced to the baseline uCO_2 spaces. To ensure the validity of the uCO_2 space, it is imperative that the undisturbed spaces CO_2 concentration is continuously monitored, to confirm that they are not being contaminated.

Figure 14 shows an aerial view of the site showing the prevailing wind direction and the experimental research spaces highlighted for clarity. The research spaces although close together were orientated in-line with the prevailing wind to minimise the risk of the increased CO_2 concentration from the eCO_2 polluting the bCO_2 spaces or uCO_2 spaces.

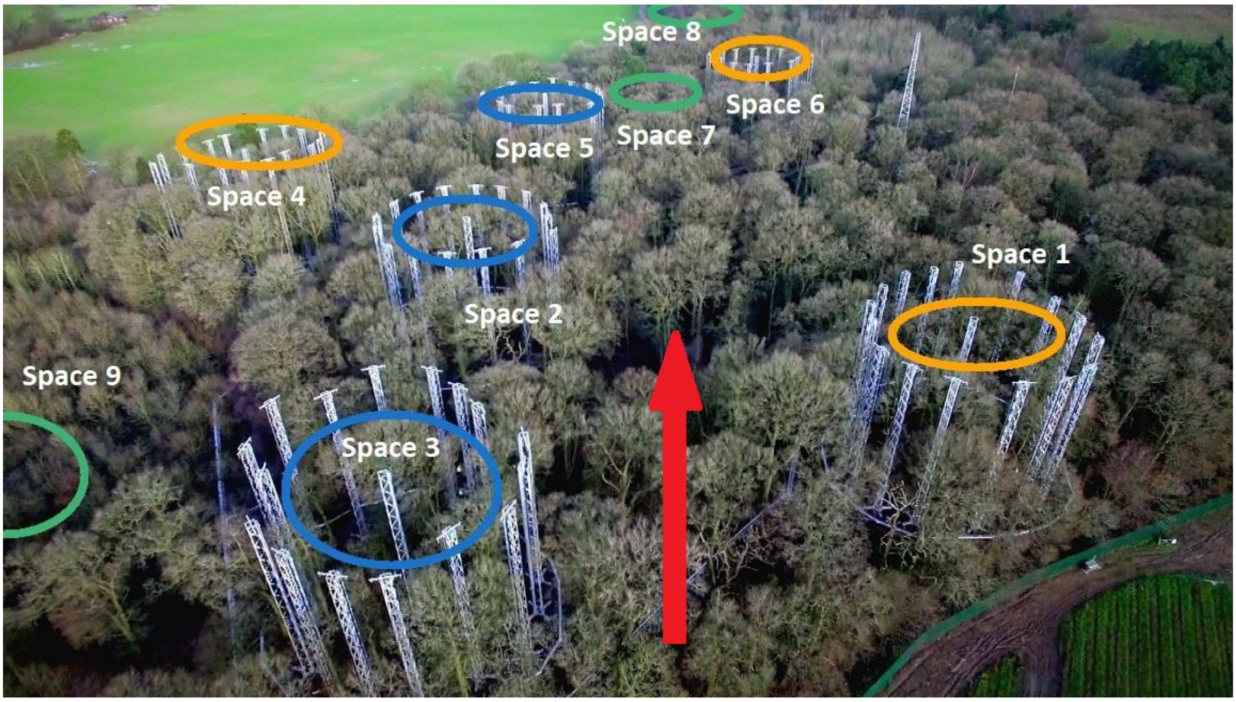

Figure 14: The BIFoR woodland. An aerial view of the site with the research spaces highlighted, the eCO_2 spaces are shown orange, the bCO_2 spaces shown blue and the uCO_2 spaces shown green, the prevailing wind direction shown by the red arrow (Hart et al., 2020).

The following table 2, compares the BNL designed tall tree FACE experiments and their designated treatment regime.

Table 2: The table provides a comparison of the BNL designed FACE experiments, showing the number of treatment, blower, and undisturbed spaces.

Project /Date of operation	Treatment	Number of enhanced spaces	Number of blower spaces	Number of undisturbed spaces
Duke **1994 – 2011**	CO_2	4	3	1
Aspen **1997 - 2009**	CO_2	3	3	0
	O_3	3		
	CO_2 and O_3	3		
Oak Ridge **1997 - 2009**	CO_2	2	3	0
EucFACE **2012 - ongoing**	CO_2	3	3	0
BIFoR **2016 - ongoing**	CO_2	3	3	3

2.6. Measurement of CO_2 in the Undisturbed Spaces

Few of the first or second generation FACE experiments have examined the undisturbed research spaces, in the plantation experiments there was no natural woodland ecosystem as the trees were planted into agricultural land (previously ploughed and fertilised) (Norby et al., 2016b). The rationale for monitoring the uCO2 spaces is discussed below.

2.6.1. Wheat FACE

One experiment that did use undisturbed spaces, identified a blower effect. At Maricopa, Arizona, the wheat FACE experiment (Pinter, 2000), observed that the ambient control research spaces (ones without blowers) plants canopy *"yellowed and then browned ca. 1 week before plants in the treatments"*. The experiment was conducted on wheat in Maricopa Arizona. During the first two years of the experiment the ambient control spaces had pipework installed to duplicate the pipe work in the enhanced spaces but, there were no blowers so no extra air movement. During this time, it was noticed that the control research spaces foliage had a different dew point and was much wetter in the early mornings. From monitoring the plant temperature and comparing the enhanced and control research spaces it was determined that during periods of very low wind speed, the enhanced space blowers were causing a rise in plant temperature. Blowers were added to the control spaces (renaming the ambient control research spaces 'blower spaces'), to ensure that the enhanced and blower areas were more comparable. Two more spaces were added as undisturbed ambient spaces (Pinter, 2000). This paper clearly demonstrates how important it is to monitor the entire ecosystem, across the different levels of control, and how one small change can have an unexpected effect across an experiment.

2.6.2. FACE Global Change Research Sites

There is little in existing literature about the previous FACE experiments uCO_2 spaces, they are generally considered inconsequential to the main experiment. This could be due to them being outside the intensively measured research spaces or that the trees were planted into agricultural land, where there was no existing woodland ecosystem.

Ambient CO_2 concentration studies conducted in woodlands have demonstrated that the local CO_2 concentration differ considerably from the global average CO_2 concentration (Wofsy et al., 1988). The currently available studies were carried out in widely differing woodland environments, mainly among young plantation trees (trees that have been planted in previously cultivated land), with inconclusive results. Finding lower than expected crop yields, when comparing chamber eCO_2 experiments with FACE, Long et al., 2006 called for more woodland, ecosystem scale experiments. Karst et al., 2023 highlighted the difference between the fertilisation experiments and those based in an existing forest ecosystem finding that the EucFACE forest emitted the majority of the 150ppm extra CO_2 introduced in the eCO_2 spaces.

The United States Department of Energy Biological and Environmental Research Advisory committee (BERAC) (2002, p. 32), argued that the *"The FACE user facilities might better be called, global change research sites"*, to put more emphasis in the wider experimentation that takes place at the FACE sites. The FACE sites are not merely CO_2 enrichment facilities but wider experimentation facilities, where all aspects of global environmental change on the entire biosphere are monitored. Continuous monitoring of the uCO_2 spaces goes hand-in-hand with this perspective.

It is intended that recording the CO_2 concentration found in the uCO_2 spaces at BIFoR, will provide an important data set, that can fill some of the knowledge gaps around the local CO_2 concentration. For the first time, it will provide an important record of the health of the wider woodland and a baseline record of how an undisturbed temperate woodland is responding to the global ecosystem changes.

2.7. Summary of Literature Review

The literature review has identified the need for experiments and particularly those using a FACE experimental approach (including BIFoR FACE, which is the focus of this research).

Experiments such as BIFoR are critical in understanding how our woodlands will respond to the predicted CO_2 rises. The literature has also identified a gap in that the existing FACE experiments either have no uCO_2 sites or in the case they do these are not monitored. Research, including that mentioned in section 2.6, identifies the importance of monitoring these sites.

The need for this at BIFoR site is further backed-up by anecdotal evidence of researchers questioning the proximity of the eCO_2, bCO_2 and uCO_2 sites and the potential for accidental cross-contamination of the CO_2.

3. RESEARCH METHODS

Reproducing the CO_2 monitoring systems from the eCO_2 and the bCO_2 spaces into the uCO_2 spaces would require large infrastructure and cause too much disturbance to the uCO_2 spaces. This chapter discusses some of the challenges involved, the construction of the equipment and the analysis techniques used in establishing what is a pollution event.

Every effort was made to minimise any disturbance to the uCO_2 space, the system was designed to monitor the CO_2 concentration vertically at five different heights in the centre of each of the three uCO_2 spaces. A haul rope was hung over the highest branch nearest to the centre of the space. This was used to haul up the three highest funnels to 21m, 18m and 15m. The 2m and 0.2m funnels were suspended from the central walkway. The funnels were connected to pipes that ran from the centre of the research space to the control cabinet positioned outside of the research space. Figure 3 shows the general arrangement of the sampling points suspended in a tree. The control cabinet containing the CO_2 analyser and ancillaries is described in more detail in the following text.

3.1. The Cabinet

The system pulls the sample air from the centre of each of the experimental research spaces through sampling pipes, back to the sampling cabinet. To minimise disturbance within the experimental space, the cabinet was mounted outside of the experimental space on the side of the existing power distribution cabinet. The pipes were laid from the centre of the space along the existing walkway, out to the remote cabinet as shown in figure 15.

Figure 15: Typical installation of the monitoring cabinet. The cabinet is mounted just outside of the experimental space; this is the cabinet at space 9 (see to figure 1 for a location map of the site).

3.2. System schematic

Each of the three sampling systems use standard widely available computer components, cabling, and standard communications protocols. Providing a cost-effective easily replicated solution. The sketch figure 16, shows the schematic arrangement and communications paths, each of the main components are discussed in more detail later.

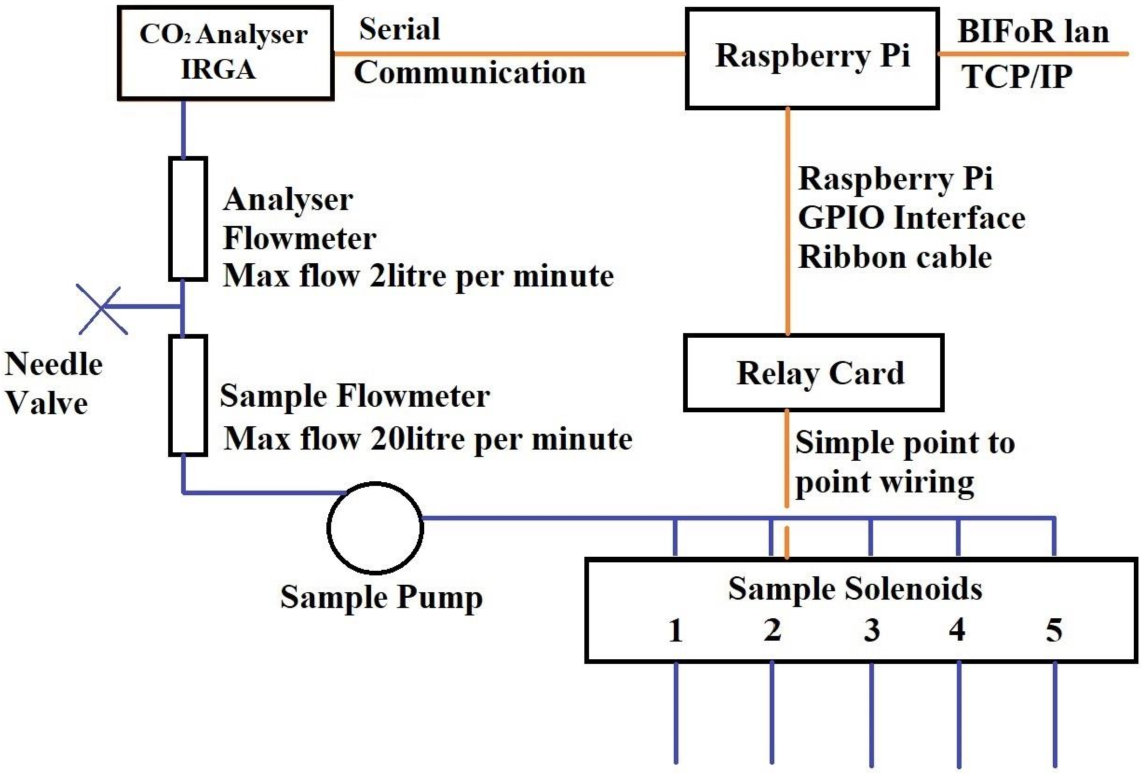

Figure 16: Cabinet schematic diagram. Schematic arrangement of the main components of each the sampling systems installed in the new cabinets, piping / gas flow path is shown blue, cabling, and electrical connections shown orange.

3.3. Inside the Cabinet

To minimise disturbance in the research space, the components of the system were mounted onto a subframe in the workshop. This allowed the entire system to be tested in the workshop before fitting into the cabinet. Thus, any swarf or debris resulting from drilling or mounting of the equipment was contained within the workshop. The fully assembled subframe was mounted into the cabinet as a complete unit. The cabinet housed the sampling system, the power supplies, power distribution, CO_2 analyser, sample pump and sample selection solenoids. Figure 17 shows the inside view of a typical cabinet, with the major components marked.

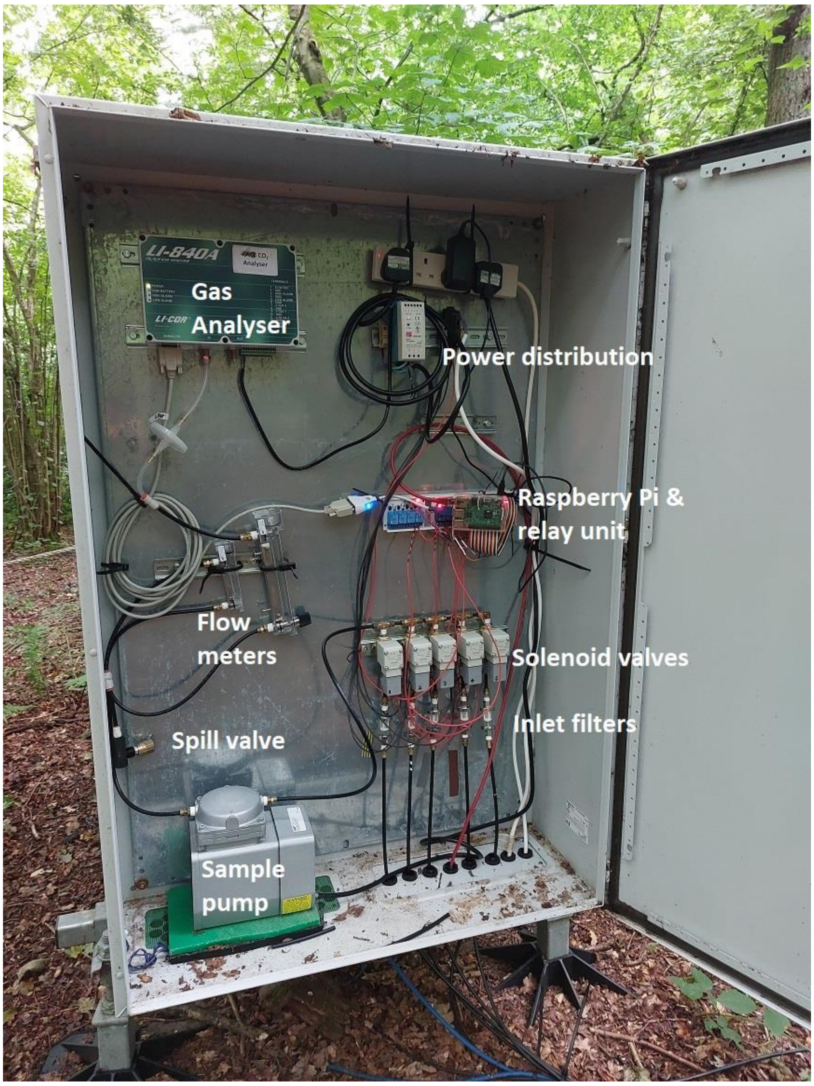

Figure 17: Inside view of one of the cabinets.

3.4. Sample Points

Each of the sampling points used a standard filter funnel manufactured by a company called Buccanan. The 60mm diameter funnel had a filter plate with multiple 0.5mm holes drilled in it, to exclude large debris and insects. The funnel reduced in size to connect to a ¼ inch black plastic pipe. The three highest sampling funnels were suspended from a cord looped over the highest stable branch, at the centre of the research space. The three funnels were attached at intervals on the cord then pulled up to the desired height (21m, 18m and 15m). The 2m and the 0.2m funnels were supported by the walkway support struts an example is shown in figure 18. It was essential that the funnels were installed pointing downward to prevent rain entering the system.

Figure 18: Example of one of the inlet funnels and pipe at 2 metres high.

3.4.1. Solenoid Valves

The sample tube extended 20 meters from the centre of the space to the sampling cabinet. The five ¼" sample tubes each connected to a glass motorcycle fuel filter, the filter was put in line to remove fine particles. Each filter was connected to the inlet of a solenoid. The five solenoid outlets were connected into a common manifold. The manifold connected to the suction side of an air sample pump. The solenoids were connected to and controlled by the Raspberry Pi, through a relay panel. The 24volt power supply was connected to the normally closed contact on the first relay, energising (opening) the first solenoid, this meant that should the Raspberry Pi controller stop or crash then the first solenoid would be open allowing a flow path for the pump. The 24 volt power was connected on the normally open contacts for the other four control relays.

3.4.2. Sample Air System

The gas analyser requires a steady flow rate of 0.5 lpm (litres per minute). The sample pipe is a ¼ inch outside diameter pipe, the internal diameter is 4mm. The longest pipe measured from the funnel to the analyser is 40m long, giving an internal volume of 0.5 l (litres). Before a fresh reliable sample could be measured at the analyser the pipe needs to be purged, running at the 0.5 lpm it would require greater than 1 minute to purge the entire sample line. To ensure an acceptable response time a Gast Pump model number DOA-P701-AA was chosen. The pump has a maximum flow rate of 10 lpm, however in this installation the actual flow rate was measured at 7 lpm due to the internal drag caused by the length and diameter of the pipe. At 7 lpm, the flow is 0.1 litres per second, at that rate the 0.5 l volume of pipe can be purged in 5 seconds. The pump inlet was connected to the solenoid valve manifold and the pump discharge to a spill system. The spill system consisted of two flow meters and a needle valve, see figure 16. The first flowmeter 0-10 lpm monitored the flow from the pump, the needle valve was adjusted to spill most of the flow sending the remaining

0.5 lpm to the analyser. The purge time in the computer program was set to 5 seconds to ensure that the longest pipe length is fully purged, and that a new sample is drawn into the analyser.

The pump outlet flowmeter showed the total flow, through the entire system. The flowmeters are checked at least once a week, a low flow at the pump flowmeter indicated that the pipes, inlet filter or motorcycle filters were blocked or that the pump had failed.

3.4.3. Infra-Red CO_2 Gas Analyser

The existing infra-red gas analysers (IRGA), used in the eCO_2 and bCO_2 spaces at BIFoR were LiCor LI840A. For consistency and to minimise spare holdings the same analysers were used.

At the centre of each of the three monitoring systems there was a LiCor LI840A nondispersive infra-red gas analyser (IRGA). The IRGA analyser principle is based on the Beer-Lambert law "There is a linear relationship between the concentration and the absorbance of the solution".

At the centre of the LI840A gas analyser is a wide band IR source, emitting wide band IR radiation, into a highly reflective gold-plated sample tube, with an IR detector at the other end, figure 19.

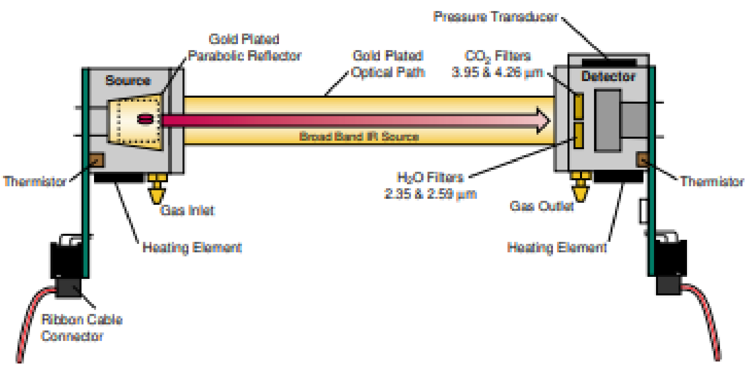

Figure 19: The IRGA sensing path. A detailed cross section of the IR source, path and detector used in the LI840A (Li-Cor Inc, 2016).

The detector head is equipped with a pressure sensor, a temperature sensor and four IR filters. There are two IR CO_2 filters one centred at 4.26 µm (micrometres) the absorption band for CO_2, the second a reference filter is centred at 3.95µm, an IR band where neither CO_2 nor water (H_2O) absorb IR. The two IR H_2O detector filters are centred at 2.595 µm and a reference filter centred at 2.35 µm (Gordon et al., 2022; Li-Cor Inc, 2016). Figure 20 shows the IR absorption spectrum of CO_2 and H_2O, and the corresponding detector filters.

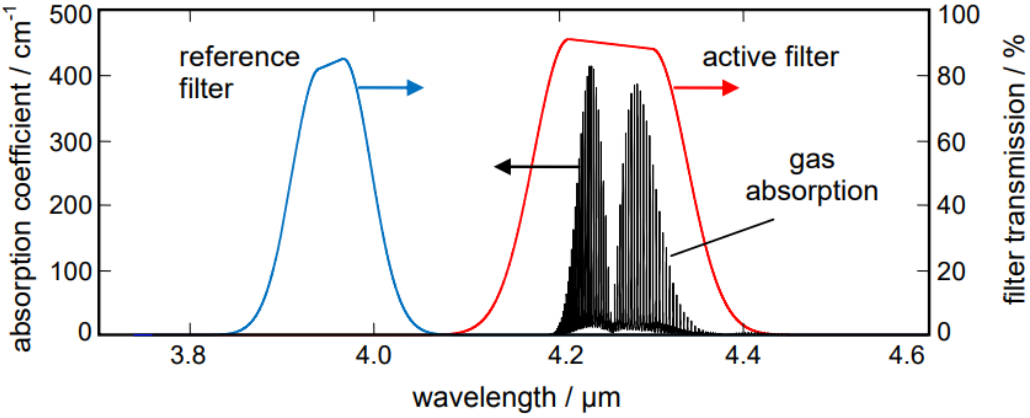

Figure 20: The Infra-Red absorption spectrum of CO_2 (Hodgkinson et al., 2013).

3.4.4. Raspberry Pi Micro-Computer

Each of the monitoring systems was controlled by a Raspberry Pi micro-computer (Pi). The Pi was chosen for this application, it is a fully functional micro-computer with built-in, video output, ethernet connections, serial ports, digital outputs, and local disk storage. When compared to other micro-controllers the Pi had more functionality and a wider choice of programming tools. An important factor when choosing the Pi was that the system would need to be open source, easily converted to use on other monitoring projects and accessible to someone who is not a computer programmer. The Pi also has a wide user community on the internet allowing for online help and support.

The Pi runs a high-level programming language python, based on open-source Linux. The python program developed for this application had a dual requirement, first to control the sample selection relays, second to interface to and record the samples CO_2 concentration from the IRGA. The program developed for this project is listed in appendix B, and is available to download from; https://github.com/NickBIFoR/uCO2Monitoring/blob/main/Ghost_MPReadW_D2.py.

The Raspberry Pi was connected to the IRGA using a standard RS-232, 3 wire serial cable. The serial interface was set to run at 9600 baud rate and with 8 data bits, no parity and 1 stop bit. The communication protocol is a based upon the eXtensible Markup Language (XML). Refer to the LI840A instruction manual (Li-Cor Inc, 2016) for full details of XML interface language.

The Pi program energised each of the five sample solenoid valves in turn. The solenoid was opened for 25 seconds, 5 seconds to purge the line and 20 seconds for the sample. During the purge the CO_2 concentration values were discarded, during the sample the CO_2 concentration was recorded every second and stored with a calculated 20 second averaged value, the data was saved to a comma space delimited (.CSV) text file for analysis later. Figure 21 shows an example .CSV file, showing the first header line, and example saved data.

The system is designed to save a new .CSV file every day, the filename is made up from the research space number, the date, in the format MP$-YYYYMMDD (where the $ is replaced by space number, the YYYY by year, MM month and DD by day of the month), this enabled easy sorting and recognition of the files. The text file was formatted with the same column structure as the bCO_2 and eCO_2 text files, to allow the same tools to be used across all the multiport system text files, eCO_2, bCO_2 and uCO_2.

```
P, DATE, TIME, SOLALT, T, F, D,IN,LY,X,Y,Z,TP,TS,WS,WD,FLOW,CSET,CF,CMP,HMP,G1,G2,G3,G4,G5,G6,G7,G8,G9,G10,G11,G12,G13,G14
9,2022/01/01,00:00:00,,,,4,5,,,18,,,,,,,,422.921,,4.26042e2,4.26481e2,4.26289e2,4.24799e2,4.23607e2,4.23929e2,4.25417e2,4
9,2022/01/01,00:00:25,,,,5,4,,,15,,,,,,,,421.09445,,4.21239e2,4.20739e2,4.20313e2,4.21431e2,4.21043e2,4.20545e2,4.20570e2
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9,2022/01/01,00:06:13,,,,4,5,,,18,,,,,,,,422.72625,,4.25097e2,4.25339e2,4.24651e2,4.25169e2,4.25452e2,4.26018e2,4.26004e2
9,2022/01/01,00:06:38,,,,5,4,,,15,,,,,,,,421.6035,,4.21247e2,4.18885e2,4.21838e2,4.21416e2,4.20072e2,4.26018e2,4.21704e2,
```
Figure 21: Example output from the Pi from 1st January 2022.

3.5. Validation of System

The system is monitored from the central control building. The central control desk connects to the Pi using a freeware program produced by RealVNC Limited. The RealVNC software is a remote desktop software, it allows the central control room computer to log onto the remote computer and enables full operation of the computer. The central control room computer is equipped with four large monitor displays, allowing all nine treatment system computers to be viewed simultaneously.

With this new system, for the first time at any FACE experiment the actual CO_2 concentration can be compared across the three-treatment regimen in real time. By visually comparing the real time readings across the experiment any instruments or CO_2 concentration anomalies could be quickly identified, and any faulty instruments rectified.

3.5.1. Regular Calibration

To ensure that the instruments are reading an accurate CO_2 concentration they are calibrated at least once every three weeks. They are calibrated with a certified calibration gas, the zero gas is 0% CO_2 concentration in Air (calibration gas supplied by Air Liquide UK, the gas is 70% nitrogen, 21% oxygen and 9% mixed trace gases).

The span or high reading is tested against a calibration gas representing air with a known CO_2 concentration for this installation the nominal value was 1000ppm CO_2

concentration in air. The gas was supplied with a high-quality analysis certificate, to 1%, the gas varied from 960ppm to 1005 ppm CO_2 concentration.

3.5.2. System Leak Test

To ensure that the correct tube was sampled in the sampling regime, the funnel at 2 metres height was blocked with a blanking plate and when the sequencer selected this port it was expected and recorded that the flow at the flowmeter went to zero. When the blanking plate was removed the flow returned to normal. The normal total flow was approximately 7 lpm, depending on the length of inlet tubing. This test ensured that the correct inlet funnel was selected and recorded and that the tube was not leaking. The 0.2 metre inlet was checked in the same way, the other higher tubes were leak tested by disconnecting and blocking the in-line tube connectors at gantry level.

3.5.3. System Response Test

The system response test was carried out to check the purge time. The purge time is set to allow the analyser, pipes, and pump within the cabinet to be cleared of the previous sample before taking a new reading. The pipe work from the cabinet to the inlet filter also need to be cleared of the static air before a sample is taken. The calibration gas of approximately 1000ppm CO_2 concentration, was setup next to the two-metre funnel, the regulator was opened enough to allow a slow flow. A pipe was extended from the gas regulator to the two-metre funnel and fixed in place. The Pi was monitored with a laptop computer. When the sequencer selected the 2m funnel, a stopwatch was started, the time to reach 800ppm was recorded at 3seconds. The reading did not reach 1000ppm, as the calibration gas pipe was not sealed to the funnel, so some fresh air was also pulled into the analyser along with the calibration gas.

3.6. Data Handling

The daily .CSV files were copied from the three Pi systems to the BIFoR local server across the local area network (lan). The BIFoR server had separate directories for each of the experimental spaces. The BIFoR server had several batch files, the first was setup to copy the daily files into one weekly file, the second batch file copied the daily and weekly files to a backup directory to be saved and the weekly file was copied into the BIFoR database directory to be added into the BIFoR general global database.

3.6.1. .CSV File Manipulation

To enable the detailed investigation of the uCO_2 MP data, some essential fields of the .CSV fields needed to be populated, these were, SOLALT (solar altitude), F (eCO_2 system treatment status 0 off ,1 for on), WS (windspeed), WD (wind direction), CSET (lowest CO_2 concentration of the three ambient spaces).

A unique field was created as the first column of all the FACE.CSV files, this was designated Date-Time, the column was populated by copying in the date in the format dd/mm/yyyy and adding the time as a text string hh:mm (the seconds were ignored). The same field was added as the first column of the uCO_2 spaces MP.CSV files.

Using the new Date-Time column as a key, it was possible to compare the FACE and uCO_2 MP.CSV files, where the date-time matched the data was copied into the uCO_2 MP.CSV files. Each of the uCO_2 .CSV files contained in excess 147,000 records; the Date-Time matched for 99.5% of the records the unmatched records were discarded as they represented an insignificant dataset.

3.7. Test Season 2021 Investigation

To determine if the enhanced CO_2 concentration was spread from the eCO_2 space into the uCO_2 spaces, the uCO_2 space CO_2 concentration was compared to lowest bCO_2 space, CO_2

concentration. The ambient CO_2 concentration changes throughout the day due to wind speed, soil respiration and the vegetation assimilation. To ensure a valid comparison between the spaces the time stamp needs to be accurate. The time stamp in the data recorded from 2021 uCO_2 spaces test installation, were found to be inconsistent. The Pi does not have an accurate clock, the clock will only operate while the Pi is running, if the system is powered down the clock will stop, after the power is restored, the clock will continue from the time the system stopped at. In the 2021 season the Pi was powered down and repowered each time the IRGA was calibrated, leading to an offset in the recorded time.

In the 2022 season the time was monitored closely (at least twice a week), the clock reset to the correct time and a note made of the difference. The system clock was always reset after the calibration was complete. Adding a battery clock module, will make the system more dependable and require less observation. Figure 22, shows a data collection timeline, highlighting major events in the data acquisition. The data collection start and the initial problems found when analysing the data.

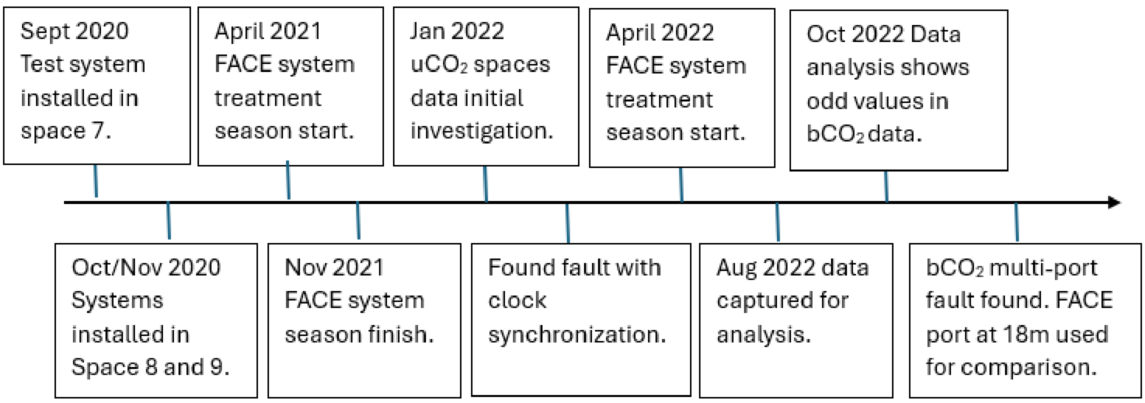

Figure 22: Monitoring timeline showing major events only. The system monitoring startup, the FACE system dosing season start and finish, the faults found with the data.

3.8. FACE Operation

The FACE experiment is programmed to ensure that the eCO_2 spaces CO_2 concentrations are stable at sunrise when photosynthesis is likely to start. The system will switch on at civil dawn when the centre of the sun is 6 degrees below the horizon, figure 23 shows the solar angle at civil, nautical, and astronomical dawn. The system has an initial start-up setting configured for the CO_2 dosing valve position; this setting enables the system to send an initial dose of CO_2 enriched air into the eCO_2 space. However, depending on wind speed the initial setting could dose too much or too little CO_2, the control system will monitor the CO_2 concentration at the centre of the space and take the appropriate control action, ensuring that the eCO_2 spaces concentration will be stable at the desired setpoint before sunrise and the start of photosynthesis.

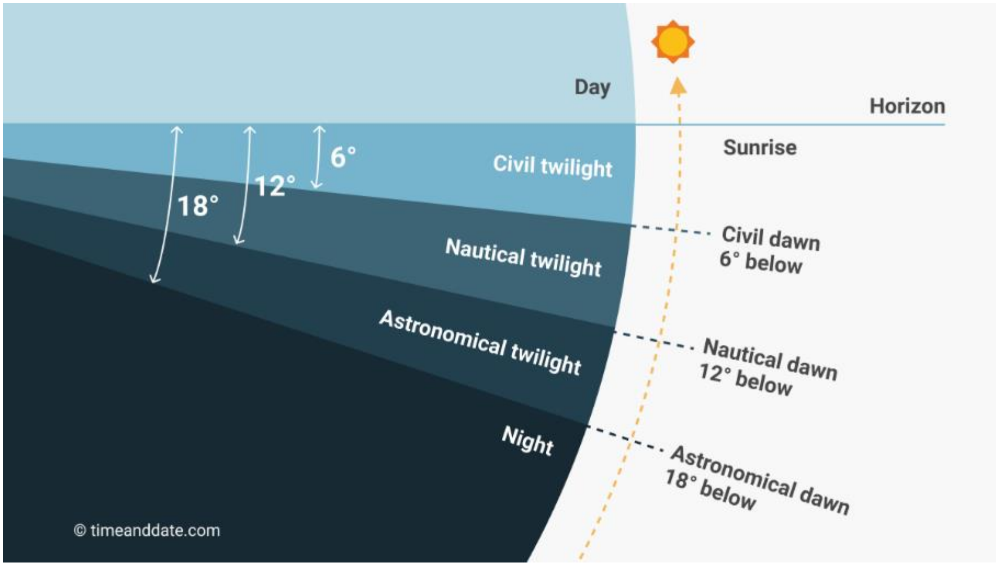

Figure 23: The point of civil dawn. Chart comparing the solar angle of Civil dawn, Nautical dawn and Astronomical dawn and the twilight zones. Civil dawn at -6 degrees from the horizon is the switch on point of the experiment ("Twilight, Dawn, and Dusk," 2023).

Pollution can only occur when the FACE system is running, the readings recorded when the FACE system was off can be discarded.

3.9. Woodland Background Diurnal CO_2 Measurement

A graph without any pollution was plotted for a 24-hour period, to show the way that the natural woodland respires. The woodland respiration is influenced by many factors, soil moisture, soil temperature, air temperature, air humidity and wind speed. Photosynthesis is influenced by many of the same parameters but with the addition of sunlight, as the primary driver. Figure 24 shows the CO_2 concentration at 18m in the centre of uCO_2 space 9, on the 10 June 2022, a day with a consistently low wind speed and no FACE enhancement (the FACE system had been shut down for operational reasons). The CO_2 concentration builds during the night, the grey box signifies night (the sun is below the horizon), the dashed vertical line is civil dawn, the time that the FACE switched on, in the eCO_2 and bCO_2 spaces. The respired CO_2 concentration peaked at approximately 445ppm around dawn.

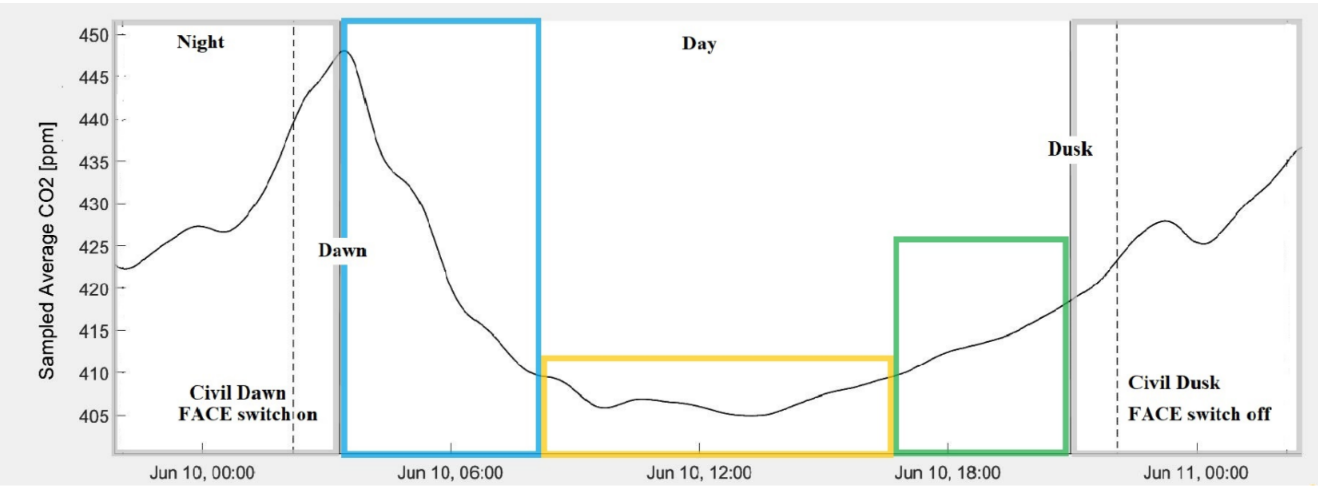

Figure 24: Diurnal CO_2 concentration, measured with FACE switched off. The graph of the CO_2 concentration at space 9, 18m high port on the 10 June 2022, the two grey boxes highlight the night-time build-up of CO_2. The blue box show how the CO_2 concentration is drawn down after dawn by photosynthesis, until reaching an equilibrium the orange box. The green box highlights where the photosynthesis rate has decreased, and the CO_2 concentration increases, then increases faster after dusk the grey box on the right.

The CO_2 was drawn down by photosynthesis, until 10am where it reached an equilibrium, the area highlighted by the blue box. From 10am until 5pm the woodland respiration and photosynthesis are in an equilibrium, where approximately the same amount of CO_2 was entering the atmosphere, as that being absorbed by photosynthesis, the yellow box. The green box is a zone where the photosynthesis rate has diminished (the photosynthesis rate diminishes typically in the afternoon after the trees have accumulated sufficient carbon, for example on a cloudy day this would occur later as the photosynthesis rate would be lower), leading to an increase in the CO_2 concentration, until dusk when the photosynthesis stops altogether (the right grey box) and the CO_2 concentration increases more rapidly. Civil dusk, FACE switch off is shown by the dashed line.

4. RESULTS AND DISCUSSIONS

In this section the initial findings are investigated, some data was removed the reason for this is discussed, along with the final analysis. The initial results showed a larger than expected difference across the nine ambient spaces, with space 3 showing a greater CO_2 concentration than expected.

4.1. Initial Data Processing

The average CO_2 concentration at the canopy, at height 18m (port 3 on the MP system), for the entire period 1 Jan to 21 Aug 2022 was calculated for the six ambient spaces. The results compared across the bCO_2 and the uCO_2 spaces and tabulated in table 3.

Table 3: The average CO_2 concentration at each bCO_2 and uCO_2 research spaces. Measured at the 18m high MP inlet port, from 1 Jan 2022 until 21 Aug 2022

	Treatment	Average CO_2 Concentration	Difference from 441ppm average
Space 2 MP	bCO_2	444 ppm	2.5 ppm
Space 3 MP	bCO_2	459 ppm	17.5 ppm
Space 5 MP	bCO_2	442 ppm	0.5 ppm
Space 7	uCO_2	437 ppm	-4.5 ppm
Space 8	uCO_2	439 ppm	-2.5 ppm
Space 9	uCO_2	428 ppm	-13.5 ppm
	Average across spaces	441 ppm	

These results show that there was a noticeable CO_2 concentration difference at bCO_2 research space 3. The bCO_2 research space 3, CO_2 concentration was 17.5ppm above the average of all ambient research spaces. The monitoring and control system at research space 3 was inspected. It was discovered that the valve controller had leaked allowing pure CO_2 into the monitoring control cabin. Some of the extra CO_2 concentration within the cabin had been drawn into the multiport analyser through a leaking solenoid manifold. Each of the 32 solenoid valves on the manifold had a small leak. When used in combination on a vacuum it allowed a small amount of air from the control cabin, now with a very high CO_2 concentration into the system, enough to cause an inconsistency in the readings. The other bCO_2 spaces 2 and 5 were checked and confirmed that they too were leaking making the other MP readings unreliable.

The bCO_2 space MP inlet port 3 at 18m, is positioned to be at the same height as the inlet to the continuous FACE CO_2 analyser. The bCO_2 FACE analyser readings were averaged and compared to the uCO_2 space MP readings and tabulated in table 4, this showed a much closer set of results.

Table 4: The average CO_2 concentration at each bCO_2 FACE port and uCO_2 research spaces. Measured at 18m high, from 1 Jan 2022 until 21 Aug 2022

	Treatment	Average CO_2 Concentration	Difference from 434 ppm average
Space 2 FACE	bCO_2	430 ppm	-4 ppm
Space 3 FACE	bCO_2	436 ppm	2 ppm
Space 5 FACE	bCO_2	434 ppm	0 ppm
Space 7	uCO_2	437 ppm	3 ppm
Space 8	uCO_2	439 ppm	5 ppm
Space 9	uCO_2	428 ppm	-6 ppm
	Average across spaces	434 ppm	

4.2. Overview of ambient space readings

The uCO_2 spaces could only be polluted when the eCO_2 dosing system was running. The overnight CO_2 concentration data when the eCO_2 was not running, was removed from the .CSV files. The data was filtered by checking the 'T' treatment column (treatment was true when the FACE, eCO_2 system was running), if it was not true the data was removed. For each space a daily average CO_2 concentration was calculated from the treatment running data. A daily average was calculated to allow a comparison between spaces, comparing the instantaneous values could give a false high value, for example if the wind speed or direction changed it could record a lower CO_2 concentration at the upwind space. Creating a daily average provided a filtered signal that smoothed out discrepancies due to wind. The CO_2 concentration quartiles and inter quartile ranges (IQR), were calculated for each space. The upper limit for the CO_2 concentration was calculated, the inter quartile three (IQR3) value plus the quartile range multiplied by 1.5 (a multiplication factor 1.5 is used to remove any equipment faults from the average). A new column was created in the .CSV file, the CO_2 concentration from each reading was copied into the new column. Each value was checked, if the measured CO_2 concentration was above the upper limit, the value was set to the upper limit. The data was analysed, and a daily average calculated for every day that the dosing system was running. A new limited averages and interquartile values were calculated from the limited values with the outliers removed. The averages and interquartile values were found to be the same, showing that the number of values greater than the high limit or lower than the low limit was insignificant to the results.

The averages, quartile ranges (IQR) and the number of days with high CO_2 recordings were calculated using the bCO_2 FACE analyser readings, the averages for the entire period were tabulated in table 5.

Table 5: The CO_2 average concentrations. The table shows the average CO_2 concentration in ppm recorded at 18m high in the bCO_2 and uCO_2 spaces, the interquartile ranges, standard deviation, the number of days monitored.

Space	**2**	**3**	**5**	**7**	**8**	**9**
Port	FACE	FACE	FACE	MP	MP	MP
Quartile 1	420 ppm	425 ppm	420 ppm	414 ppm	416 ppm	405 ppm
Quartile 2	426 ppm	433 ppm	428 ppm	427 ppm	424 ppm	413 ppm
Quartile 3	440 ppm	446 ppm	441 ppm	452 ppm	437 ppm	425 ppm
IQR	20 ppm	21 ppm	21 ppm	37 ppm	21 ppm	20 ppm
Std deviation	24 ppm	24 ppm	22 ppm	31 ppm	29 ppm	27 ppm
Mean	430 ppm	438 ppm	434 ppm	439 ppm	432 ppm	420 ppm
Highest Outlier	1003 ppm	1014 ppm	1151 ppm	989 ppm	1106 ppm	704 ppm
Lowest outlier	391 ppm	393 ppm	393 ppm	386 ppm	389 ppm	382 ppm
Days monitored	143	143	153	142	140	140

The 18m CO_2 concentration was plotted in a box plot for each space, see figure 25. The boxplot provided a visual representation of the normal distribution and the range of the values recorded. The plot showed the mean CO_2 concentration for each experimental space represented by a horizontal bar, a box represented the IQR for that space with a vertical line representing the spread of values. Space 7 showed the widest variation with a IQR of 37ppm, all other spaces had an IQR of 20-21ppm.

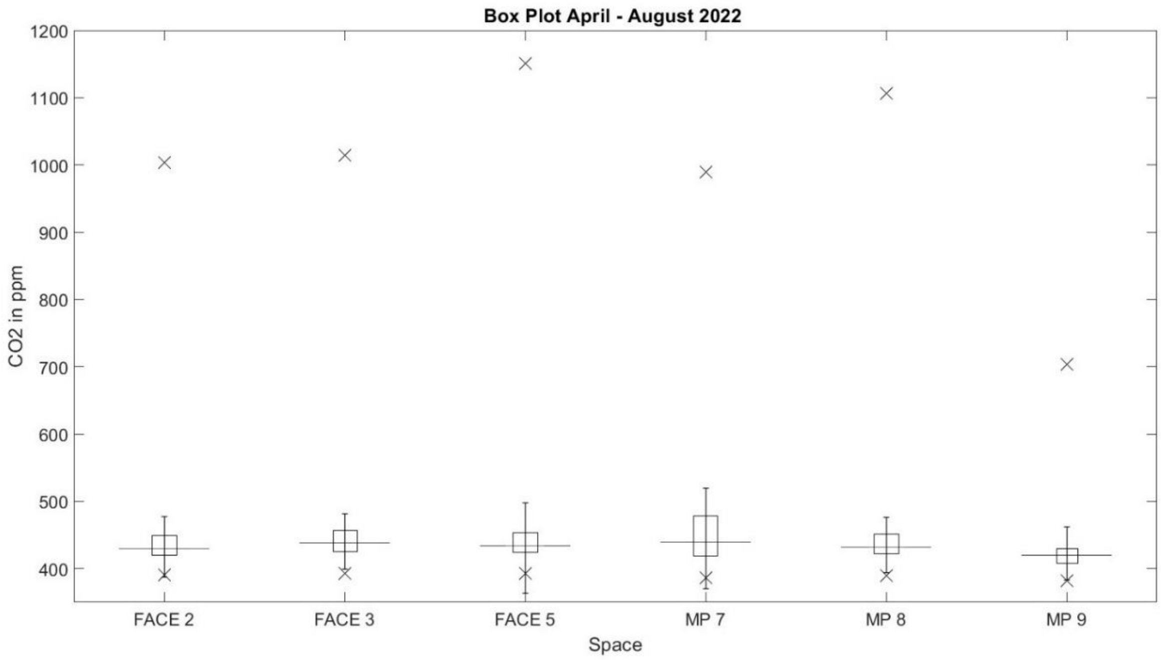

Figure 25: Boxplot of the CO2 concentration in ppm, April to August 2022. Mean Values shown with a horizontal line, the box shows the variation between the quartile 1 and 3 concentration. The vertical line shows the minimum and maximum concentration. The outliers are shown with an X.

4.3. Finding Pollution Events

The IRGA analysers had a specified accuracy to 1.5% of reading (Li-Cor Inc, 2016), which could result in a worst-case error of 6.255 ppm analysing a sample of ambient air (the global average ambient CO_2 concentration was 417 ppm in 2022 (NOAA, 2023)). When comparing two analyser values against each other this could be 6.255 ppm per analyser, representing a worst case of 12.51 ppm (3%) between values read, when analysing the same concentration of CO_2.

To allow for the analyser potential error and to allow a deadband the limit for a good reading was defined as a reading that was less than 5% above the lowest bCO_2, CO_2 concentration (5% of 417 ppm gave a result of 20.85 ppm this was rounded to 21 ppm for simplicity). When the data was analysed any day that had a daily average greater than 21 ppm (5%) above the lowest bCO_2 space, it was flagged as a day requiring investigation, table 6 shows the number of days identified.

Table 6: The total number of days monitored for each space and the number of days identified as having CO_2 concentration greater than 21ppm (5%) above the lowest bCO_2 concentration.

Space	**2**	**3**	**5**	**7**	**8**	**9**
	FACE	FACE	FACE	MP	MP	MP
Days monitored	143	143	153	142	140	140
Number of days with CO_2 >21ppm above lowest blower	5	2	1	36	4	0

4.3.1. Space 7 days with extra CO_2

The FACE daily logbook (the FACE daily logbook is the engineering record of plant failures calibrations and interventions) noted that the space 7 sample pump had failed on 29 July 2022, the pump was replaced and back in service again on the 9 Aug 2022. During this period the pump had been switching on and off due to thermal overload. When the sample was static in the IRGA the apparent CO_2 concentration had increased, when the pump switched back on the CO_2 concentration had returned to normal. During this period the pump had been switching on and off causing a random CO_2 concentration to be recorded. These 10 days were removed from any further analysis. The FACE daily logbook also identified the 26 April 2022 as an equipment failure date, the IRGA had failed and was replaced on the 27April. In total 11 days were excluded from the space 7 analysis, leaving 25 days out of the 131 monitored requiring further investigation.

All the space 7 days with CO_2 concentration greater than the 5%, above the lowest bCO_2 concentration were identified in table 7, the days with equipment failures are struck through.

Table 7: Space 7 dates recorded with high CO_2 concentrations. Days that the average CO_2 concentration at space 7 were greater than 21ppm (5%) above the lowest bCO_2. Dates with a line through are days that were logged as equipment failures.

April	June	July	August
20/04/2022	03/06/2022	11/07/2022	~~01/08/2022~~
21/04/2022	04/06/2022	12/07/2022	~~02/08/2022~~
22/04/2022	05/06/2022	17/07/2022	~~03/08/2022~~
23/04/2022	09/06/2022	18/07/2022	~~04/08/2022~~
24/04/2022	10/06/2022	~~31/07/2022~~	~~05/08/2022~~
~~26/04/2022~~	23/06/2022		~~06/08/2022~~
27/04/2022	24/06/2022		~~07/08/2022~~
28/04/2022	25/06/2022		~~08/08/2022~~
	26/06/2022		~~09/08/2022~~
	28/06/2022		10/08/2022
			11/08/2022
			18/08/2022
			20/08/2022

4.3.2. Space 8 days with extra CO_2

There were only four days flagged, when space 8's daily average CO_2 concentration was greater than 21ppm (5%), above the lowest bCO_2 concentration. These were tabulated in table 8 and then plotted graphically. During the investigation it was discovered that there had been a problem with the network infrastructure on the 18 May 2022, the ambient CO_2 concentration had not been recorded correctly in the space 8, that day was removed from further analysis leaving just 3 days out of 139 requiring further investigation.

Table 8: Space 8 days recorded with high CO_2 concentrations. Days that the average CO_2 concentration at space 8 were greater than 21ppm above the lowest average. The date with a line through is the date of the network failure.

May	July
01/05/2022	12/07/2022
~~18/05/2022~~	18/07/2022

4.4. Vertical CO_2 profile

The uCO_2 spaces vertical profile figure 26, were plotted to investigate how the CO_2 concentration varies vertically at the centre of each space. The average CO_2 concentration for the entire measurement period across all five intake funnels was calculated for each space. The average CO_2 concentration for each port for the entire measurement period was then compared to the average for that space. This normalised each space, the average became the zero point on the x axis of the plot. The difference from the average showed a good correlation to the expected response:

- The 0.2m port showed the highest concentration above the average, indicating that the soil and litter on floor of the space was respiring, it was a source of CO_2.
- The 2m port recorded a higher-than-average concentration indicating that a fraction of the respired CO_2 was held under the tree canopy, a portion had been absorbed by understory (the short vegetation found in the spaces) photosynthesis or dispersed by the under-canopy air currents.
- The 15m lower canopy port showed a slightly less CO_2 concentration than the average, indicating the CO_2 was being absorbed by the lower canopy.
- The 18m port (the FACE equivalent port), also showed a slightly higher CO_2 concentration than the 15m port.
- The 21m port recorded the lowest CO_2 concentration, the tree canopy had absorbed the natural CO_2 emitted from the woodland floor.

Space 7 showed the widest variation in results (identified by the +), Space 9 (identified by the X) showed the closest spread of results. There are several factors that could influence this reading, the upper canopy being more exposed to the wind in space 7, and space 9 being the most sheltered. That the space 7 had received the highest quantity of enhanced CO_2. Or due to different composition of the soil, litter, or understory composition in the spaces (documenting the different soils/forest floor composition is not part of this study).

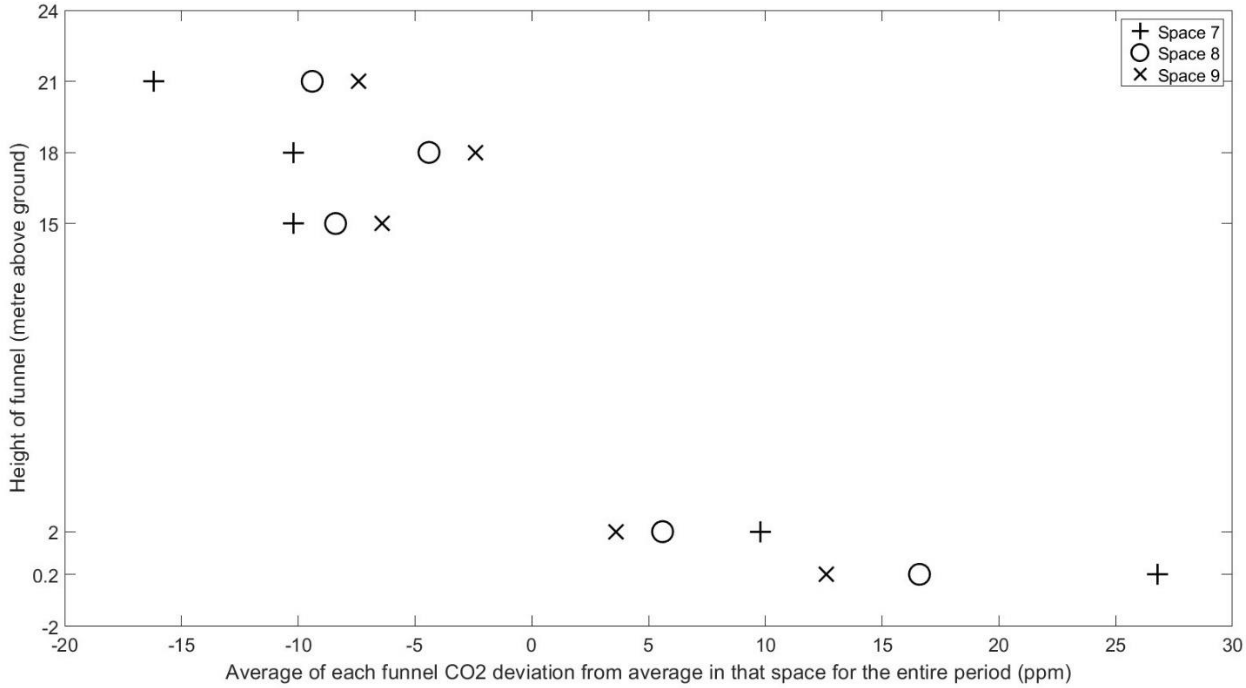

Figure 26: Each port, CO_2 concentration deviation (in ppm), from the average of that space. Space 7 intake averages shown +, space 8 shown O and space 9 shown X. Highlighting how the woodland soil is respiring, emitting CO_2 into the environment and the tree canopy is absorbing CO_2.

4.5. Space 7 Enrichment

Space 7 showed a higher CO_2 concentration than the 21ppm limit, on 25 days of the 131 days measured. This equated to 19% of the time, but the enrichment was only minor at only 14% of eCO_2 setpoint during these events. The following sections describe the source of the CO_2.

4.5.1. Space 7 Radial plot East

To determine the source of the extra CO_2, the CO_2 concentration was plotted on a radial plot where the angle of the segment was the wind direction during the pollution event. The length of the bar representing the number of records at that concentration. The pollution event shown in figure 27, is the space 7 CO_2 concentration minus the lowest ambient concentration on the 1 June to the 5 June 2022, a typical enrichment event.

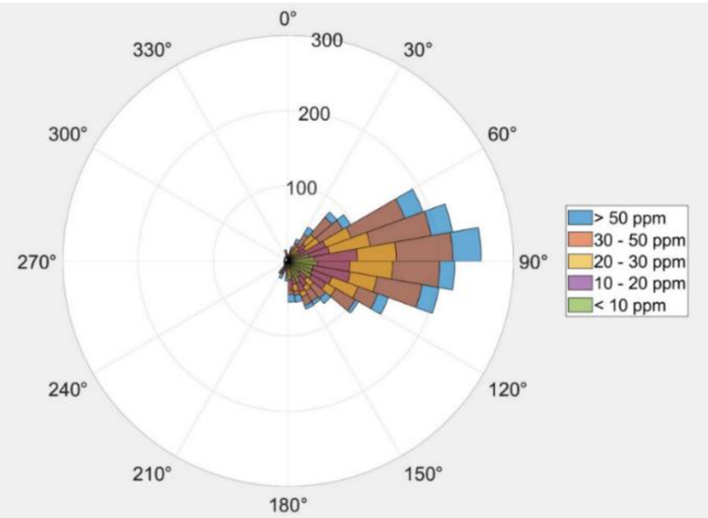

Figure 27: Typical radial plot at space 7 (Easterly). The CO_2 concentration is plotted in the direction the wind was coming from, the length bar represents the number of readings of that concentration above the lowest ambient concentration, from 1 June 2022 until 5 June 2022.

For 52% of the high readings, the wind was coming from an easterly direction, space 6 an eCO_2 space, is 50m to the east of space 7. The wind easily carried the enhanced CO_2 from space 6 into space 7 due to the proximity of the spaces, leading to a prolonged, but low-level enrichment. Figure 28 shows a typical pollution event, showing the CO_2 concentration at 18m, minus the lowest ambient on the 4 and 5 June 2022.

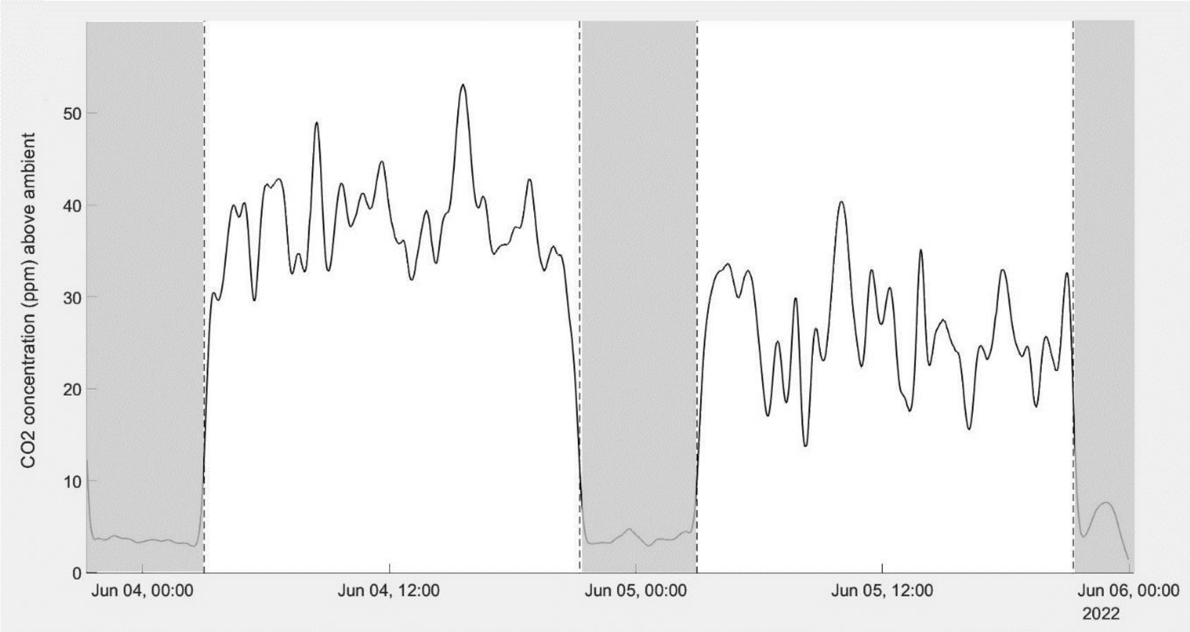

Figure 28: Graph of typical enhanced CO_2 space 7 (Easterly). The graph shows the space 7 CO_2 concentration minus the lowest ambient concentration, on the 4 and 5 June 2022, the shaded areas show when the FACE experiment was off.

4.5.2. Space 7 Radial plot Southwest

For 48% of the high readings the wind was in a south-westerly direction. The enhanced CO2 concentration was plotted on radial plot figure 29 shows a typical south-westerly enrichment, from the 9 and 10 June 2022. Space 1 an eCO_2 space is 150m southwest from space 7.

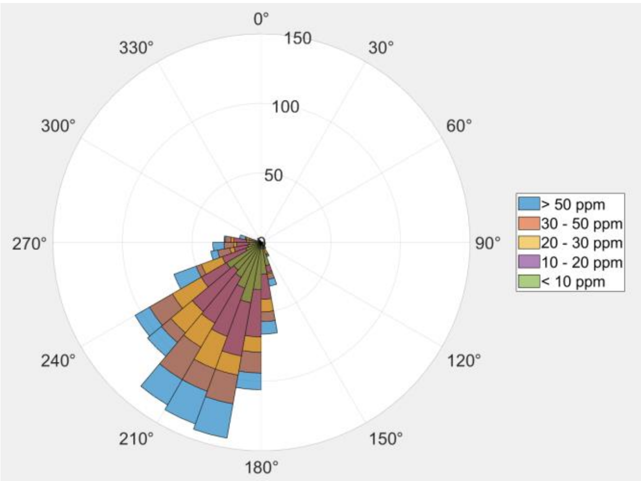

Figure 29: Typical radial plot at space 7 (South-south-westerly). The CO_2 concentration is plotted in the direction the wind was coming from, the length bar represents the number of readings of that concentration, above the lowest ambient concentration, on the 9 and 10 June 2022.

The South westerly pollution was much more erratic, the wind carried the enhanced CO_2 across 150m of woodland and rough terrain, leading to an erratic trace with higher peaks. Figure 30, shows an example of pollution with the wind in the southwest, from the 9 and 10 June 2022, the graph shows the pollution at space 7, the recorded CO_2 concentration minus the lowest ambient. The peaks of almost 100ppm CO_2 concentration are significant, but their duration is only short, with the daily average less than 30ppm above the lowest average.

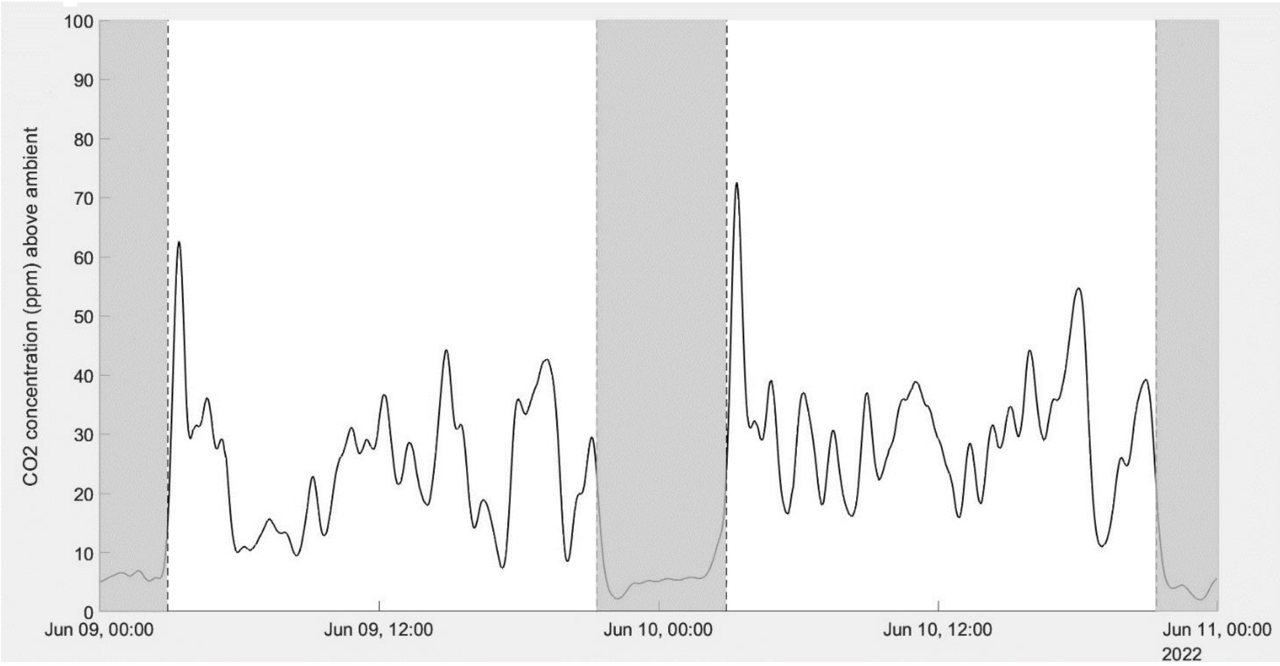

Figure 30: Example graph of the enhanced at space 7 (South-south-westerly). The graph shows the space 7, CO_2 concentration minus the lowest ambient concentration, on the 9 and 10 June 2022. The shaded areas show when the FACE enrichment was off.

4.5.3. Space 7 Overview

The vertical, CO_2 concentration at space 7 was examined for the days that were identified as higher than average. The greatest concentration of enrichment was found to be under the canopy, figure 31 shows a typical enhanced day, the 17 July 2022. The graph shows that most of the enrichment occurred at the 0.2m high the green trace and at 2m high purple trace. At approximately 19:00 the 15m and 18m high ports both show a significant increase, in the CO_2 concentration, the enrichment at canopy height is relatively short returning to normal again by 21:00. The under-canopy enrichment has less impact on the Oak trees but could be impacting the understory experiments.

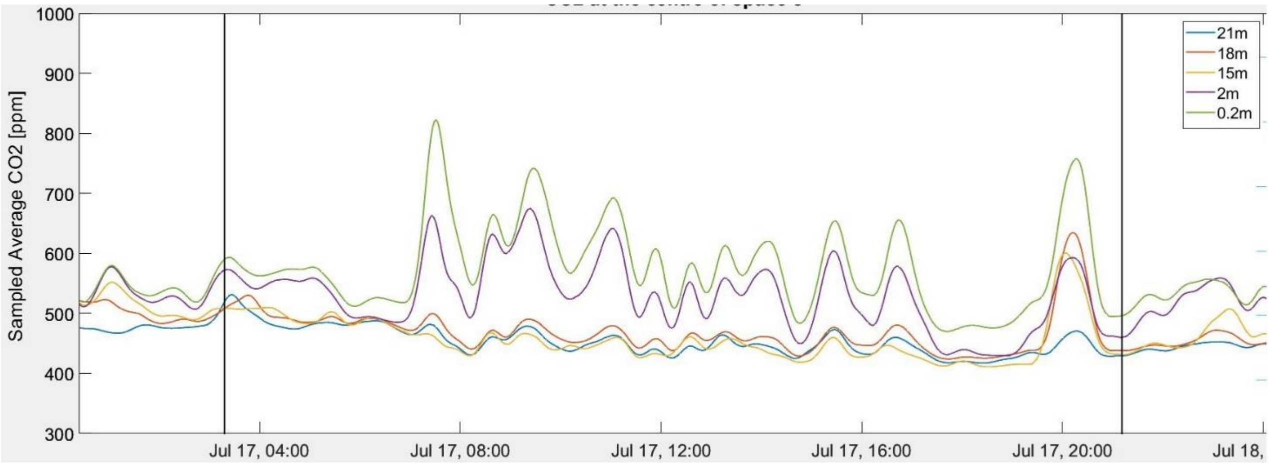

Figure 31: A typical example of space 7 pollution event. The graph shows the CO_2 concentration on the 17 July 2022, showing the five points vertically at the centre of the space 7. 0.2m green, 2m purple, 15m yellow, 18m red and 21m blue. The peaks in the trend show enhanced CO_2 blown into the space, mostly under the canopy.

4.5.4. Space 7 Tabulated results

All the days at space 7, that were greater than 21ppm above ambient, were recorded into table 9. This showed that the worst enrichment days were in April before the full flush of leaves. The extra CO_2 received in April, was just 5% of the monitoring period. The average enrichment was 24% of the eCO_2 setpoint, for 67% of the daylight hours.

The high CO_2 days in June, July, and August, represented 14% of the monitoring period. The CO_2 enrichment was a smaller dose at just 17% of the eCO_2 setpoint, for 46% of the daylight hours.

Of the 131 days monitored 19% of the days measured received extra CO_2. While the duration and concentration of the pollution was not substantial, any extra CO_2 in the undisturbed spaces is now recorded and can be used to support the wider BIFoR FACE eCO_2 experiment.

Table 9. Space 7, table of days higher than ambient CO_2 concentration. The table lists the days when the average CO_2 concentration was more than 21ppm above ambient, the daylight duration and duration of pollution.

Date	Average CO_2 concentration above ambient ppm	Percentage of eCO_2 setpoint	eCO_2 runtime hrs: mins	Percentage of runtime with high CO_2
20/04/2022	33 ppm	22 %	15:32	51 %
21/04/2022	37 ppm	25 %	15:37	70 %
22/04/2022	38 ppm	25 %	15:41	72 %
23/04/2022	44 ppm	30 %	15:45	82 %
24/04/2022	41 ppm	27 %	15:49	76 %
27/04/2022	28 ppm	19 %	16:02	60 %
28/04/2022	27 ppm	18 %	16:06	57 %
03/06/2022	27 ppm	18 %	18:15	58 %
04/06/2022	37 ppm	25 %	18:18	82 %
05/06/2022	25 ppm	17 %	18:21	58 %
09/06/2022	24 ppm	16 %	18:24	38 %
10/06/2022	29 ppm	19 %	18:27	50 %
23/06/2022	25 ppm	16 %	18:35	48 %
24/06/2022	23 ppm	16 %	18:35	47 %
25/06/2022	25 ppm	15 %	18:34	38 %
26/06/2022	26 ppm	17 %	18:34	44 %
28/06/2022	25 ppm	17 %	18:32	42 %
11/07/2022	25 ppm	16 %	18:08	43 %
12/07/2022	22 ppm	14 %	18:06	35 %
17/07/2022	27 ppm	18 %	17:52	44 %
18/07/2022	26 ppm	17 %	17:46	42 %
10/08/2022	37 ppm	25 %	16:29	58 %
11/08/2022	22 ppm	14 %	16:23	37 %
18/08/2022	24 ppm	16 %	15:53	40 %
20/08/2022	23 ppm	15 %	15:45	33 %

4.6. Space 8 Enrichment

Space 8 CO_2 concentration was higher than 21ppm above than the lowest ambient on only 3 of the 139 days measured, just 2.2% of the measured days. All three days were plotted on a radial plot, figure 32. This showed that on all three days the wind had been in a Southerly direction, indicating that the CO_2 had originated in the eCO_2 space 6.

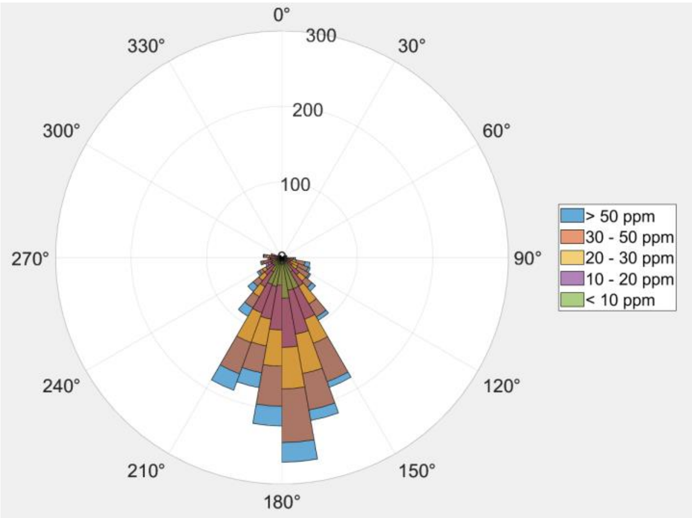

Figure 32: Radial plot of CO_2 concentration at space 8 on the three high days. The CO_2 concentration is plotted in the direction the wind was coming from the length of the bar indicate how many values were recorded at that concentration.

4.6.1. Space 8, 18 July plot

The 18 July 2022 was identified as a day with a high CO_2 concentration, figure 33 shows the concentration for 24 hours at five heights. The graph initially showed a good correlation to the expected pattern, with the green trace the 0.2m intake reading the most CO_2. After 6am there was a substantial increase in the concentration at the 0.2m intake (up to a maximum of 700ppm), at the same time the other ports increased but showed a smaller concentration, 2m (560ppm), 18m (520ppm) and the 21m (470ppm), the port at 15m, the yellow line, did not respond, the pipework was suspected blocked. The canopy port at 21m received very little of the extra CO_2, this pattern is indicative of extra CO_2 from space 6 blowing under the canopy into space 8.

From 13:00 to 16:00 there is a steady period where the concentration varies between 430ppm and 450ppm. After 16:00 there is a significant increase in the CO_2 concentration at the 18m port up to 859ppm, the other ports showed high concentrations too; 669ppm at 0.2m, 586ppm at 21m and 522 at 2m, 7 CO_2. The CO_2 concentration returned to normal after 19:00, although this event was a significant elevation of the CO_2 concentration it was for 3 hours. The pattern of the extra CO_2 concentration indicated that the extra CO_2 was blown through space 6 and into the canopy of space 8, this was however for only a very short period.

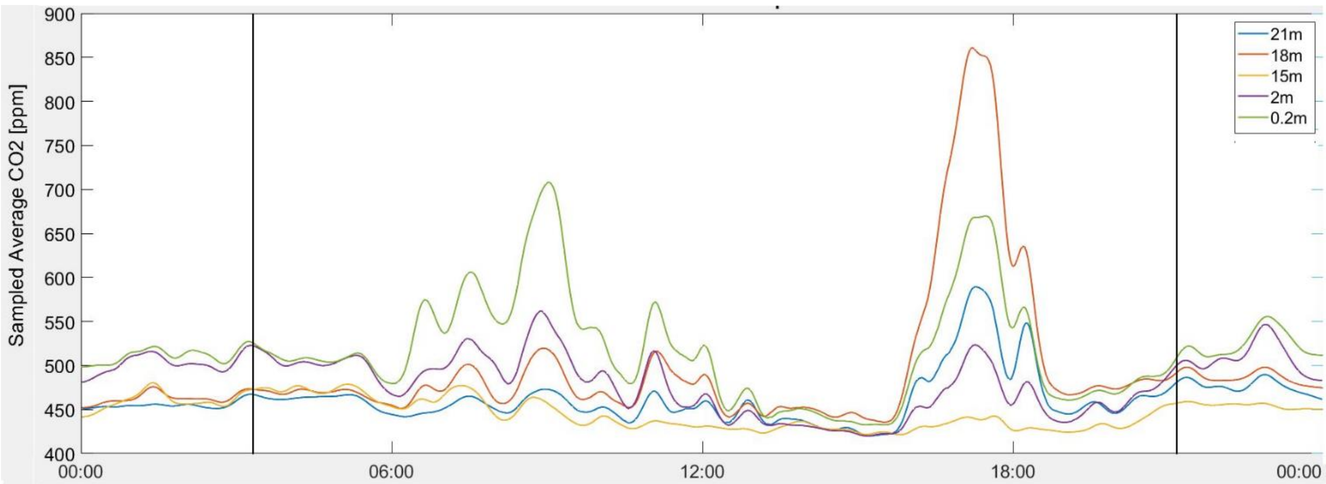

Figure 33: CO_2 concentrations plotted for 24 hours on the 18 July 2022. The graph shows how the extra CO_2 is blown into space 8, the traces and ports are arranged at the centre of the space at the following heights: green trace 0.2m port, purple trace 2m, yellow trace 15m, red trace 18m and blue 21m. The left black vertical line show when the FACE experiment treatment was switched 'ON' and the right line is FACE switching 'OFF'.

4.6.2. Space 8 Tabulated Results

The days recorded with a high CO_2 were tabulated into table 10, showing that the extra CO_2 concentration was very minimal and only occurred on three days of the entire measurement period.

Table 10: Space 8, table of days higher than ambient CO_2 concentration. The table lists the days when the average CO_2 concentration was more than 21ppm above ambient and the daylight duration.

Date	Average CO_2 concentration above ambient	Percentage of eCO_2 setpoint	eCO_2 runtime hrs: min	Percentage of runtime with high CO_2
01/05/2022	24 ppm	16 %	16:18	56 %
12/07/2022	27 ppm	18 %	18:06	56 %
18/07/2022	26 ppm	17 %	17:46	55 %

The number of days that showed a higher CO_2 and the duration of this enrichment was not at all significant. This research has shown that there is no substantial pollution at space 8.

4.7. Space 9 Below Ambient

Research space 9 an uCO_2 space was consistently 10ppm below the average of the other ambient research spaces, this may be due to the positioning of the research space. Space 9 had a more open canopy and was situated on the southwest side of the site making it more susceptible to the prevailing south westerly wind, the open canopy allowing the respired CO_2 concentration to blow away more easily.

4.8. Fan Disturbance Measurements

At the initial design stage of the project, it was recognised that the blowers in the ambient bCO_2 spaces could promote mixing of the overnight respired CO_2 concentration. At previous FACE experiments it has been demonstrated that the forced air blowers changed the dew point and the humidity in the eCO_2 and bCO_2 spaces under very still conditions. It has not been investigated how the blowers in the experimental spaces alter the static respired CO_2 concentration. If the bCO_2 blowers were causing a disturbance, then it is expected that the under canopy, bCO_2 spaces would record a lower CO_2 concentration than the uCO_2 areas. Figure 34 shows an example week, from 30 May to the 6 June, the averaged CO_2 concentrations at 15m, under the canopy, in all bCO_2 and uCO_2 spaces was plotted. The graph shows how all the spaces respond to the woodland respiration in very similar way. In the greyed out night-time areas, the concentration traces are very close together. Some of the daytime peaks and some of the randomness seen in the traces are because of the ambient spaces MP sample contamination, space 3 coloured red is often the highest, but this is probably due to space 3 MP system having the biggest leak.

There was no discernible pattern in the under canopy. The bCO_2 traces were random, this was primarily due to the leaking ambient monitor system. It is recommended that the under-canopy response examination, should be repeated now that the MP leaks have been fixed.

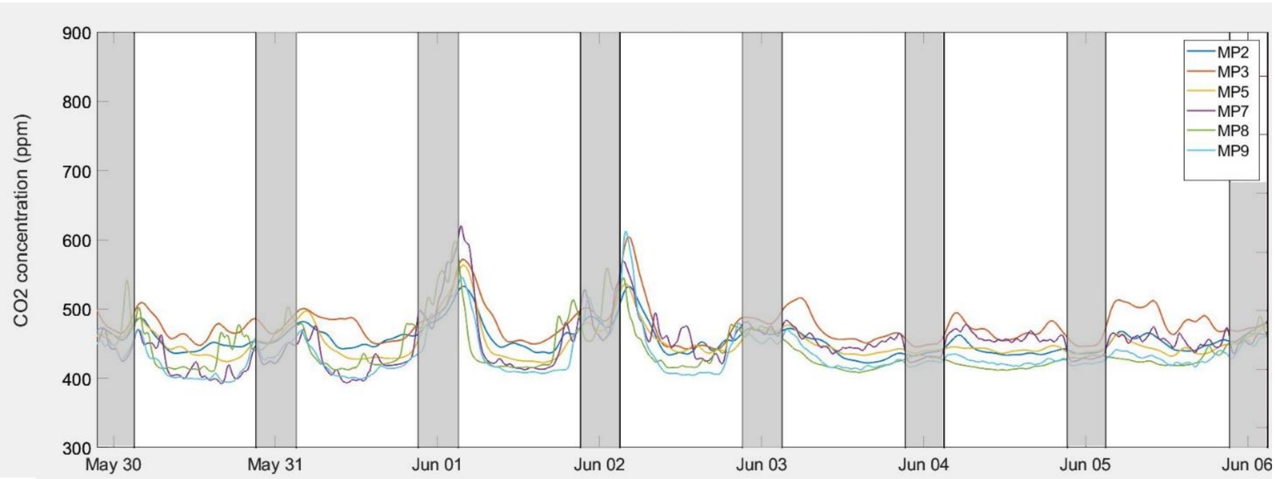

Figure 34. The CO_2 concentration measured at 15m high in bCO_2 and uCO_2 spaces. The CO_2 concentration was measured at 15m above ground, just below canopy, from the 30 May, until the 6 June 2022. The traces show the CO_2 concentration in the bCO_2 spaces, blue - space 2, red – 3, orange – 5 and the uCO_2 spaces purple - 7, green – 8, blue – 9.

4.9. Discussion

To get a clearer picture of the uCO_2 spaces, this research and analysis should take place over several years. This study was constrained by the duration of the master's by research degree, time frame. This first treatment period recordings were unreliable due to the clock discrepancies previously mentioned.

Undertaking this research on a single treatment period does not allow for the full range of weather conditions or for an herbivore event to be analysed. Extreme weather heat or cold and prolonged wind from any direction other than the south-west could have a large impact on the potential for pollution between spaces. Climate patterns such as El Nino, can have a large impact on the wind patterns but do not occur every year. This experiment should be extended to cover at least two El Nino weather events.

In 2018 BIFoR woodland was subjected to an extreme herbivore event, several large oak trees on the SW side (the upwind side) of the forest were stripped of their leaves by an infestation of winter moth caterpillar. The trees did recover with a second flush of leaves, but they were smaller than the original leaves. This had a large impact on the wind flow through the forest and the CO_2 consumption at the eCO_2 spaces. Unfortunately, at that time there was no CO_2 monitoring in the uCO_2 spaces, so it is not known how far the CO_2 plume reached. To ensure that these types of events are captured the uCO_2 monitoring should be extended as long as possible.

To enable a more thorough comparison and examination of the 18m canopy variations, the system could be reconfigured to continuously record the 18m inlet port, for the 20 minutes that the system currently waits between readings. This could enable a greater understanding of how the wind patterns influence the canopy CO_2 concentration.

This research only looked at the uCO_2 experimental spaces themselves, this research could be extended to the other areas of the forest currently not being measured. Those spaces between the experiments could be experiencing enhanced CO_2 from the eCO_2 spaces plume. Understanding how the plume migrates and disperses through the rest of the woodland could be useful to other research, for example, helping to understand how a forest fire may migrate. It could also be used to discover how far the downwind the CO_2 plume extends beyond the eCO_2 spaces, this may be useful when setting out research spaces in any new FACE experiment.

4.10. Other Outcomes Flux Tower CO_2 Measurement

The CO_2 analyser at the top of the BIFoR Flux tower (the 40m tower installed to monitor the CO_2 concentration and fluxes above the woodland) had been calibrated but the CO_2 concentration was showing wide variation over a few minutes. Another system, preferably ground based, was needed to verify that the readings were correct. It was possible to setup a temporary CO_2 monitoring system, at no cost by utilising the spare BIFoR equipment. The development Pi used to test programs was connected to a spare IRGA and a spare sample pump. The sample pump drew air from the top of the 40m Flux tower using existing pipework.

The Pi program generated for the uCO_2 monitoring system was modified, to remove the selection sequence and to record three values, a 5 second instantaneous value, a 1-minute average and a 5-minute average reading. The CO_2 concentration recorded at the Pi proved that the analyser at the top of the tower was incorrect. It also showed how the extra CO_2 dosed at the enhanced FACE systems was blowing above the woodland canopy. Figure 35 shows a graph of the CO_2 concentration recorded at the top of the 40m Flux tower, the erratic part of the graph is enhanced CO_2 blowing above the woodland. The grey shaded areas are night-time when the FACE systems are shutdown, during these periods the CO_2

concentration fluctuates by a small amount about 2-3 ppm. When the FACE enrichment is on the fluctuations can be as much as 30 ppm, the lowest readings equating to the normal woodland CO_2 concentration and the high points showing the extra wind-borne CO_2 from the enhanced areas.

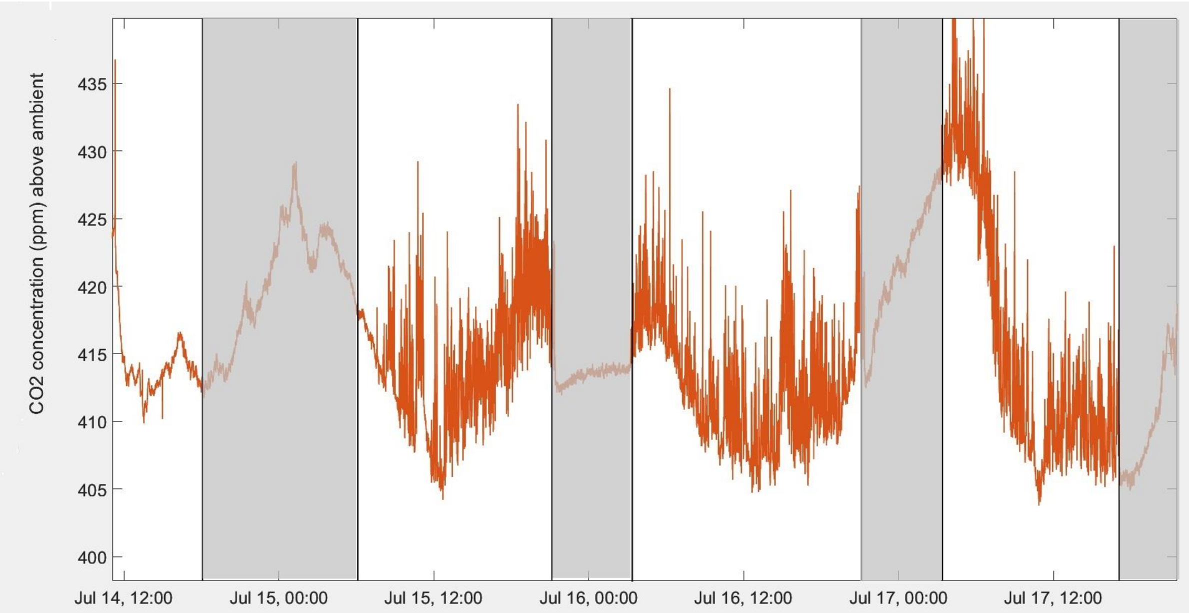

Figure 35: Flux tower 40m high CO_2 concentration. Graph showing the CO_2 concentration at BIFoR above the tree canopy at 40m high. The grey areas show when the FACE enrichment was shutdown, the orange trace is the graph of the measured CO_2, showing peaks of 30ppm above the expected level.

5. CONCLUSIONS

The objective of this research was to examine the background CO_2 concentration found within the uCO_2 spaces at BIFoR FACE experiment. A CO_2 monitoring and recording system was designed, constructed, and installed within the uCO_2 spaces. Despite the initial challenges with the time synchronisation, the system was corrected and has recorded valuable data. The monitoring system functioned effectively, undergoing regular checked and calibration. Analysis of the uCO_2 data revealed a previously unnoticed issue with the main FACE experiments MP system, that has now been corrected.

Due to the time constraints, only partial seasonal data was analysed, leaving the complete data set available for future research. Initial findings suggest no significant difference in CO_2

concentration between bCO_2 and uCO_2 spaces at the 18m high port. Confirming that the bCO_2 spaces can be used as the ambient CO_2 concentration for the FACE setpoint calculation.

Although the investigation of under-canopy CO_2 concentration was hindered by the leaks within the bCO_2 monitoring systems, the data is recorded and is available for further research.

Space 9 was unaffected by the FACE enhancement experiment showing a consistently lower CO_2 concentration than any of the other five ambient spaces. Space 9 was situated on the Southwestern side of the forest (the prevailing windward side) with a more open canopy, allowing any respired CO_2 to be dispersed more easily.

Space 8 showed little pollution with only 3 days recording a high reading, just 2.2 % of the monitoring period. The wind pattern indicated that the enhancement was from eCO_2 space 6. Space 8 will continue to be monitored to ensure that the space remains relatively free from enhanced CO_2.

Space 7 experienced the worst enrichment at around 15% of the eCO_2 setpoint, for 25 of the 131 days measured, 19% of the monitoring period. The wind patterns indicated that the enhancement was from eCO_2 space 6 and eCO_2 space 1. The enhancement that was shown to have been from space 1 was unexpected, due to the distance between spaces and the amount of flora between the spaces.

This dataset has and will continue to provide an important background underpinning the wider BIFoR experiments. This study only monitored the period of spring, summer 2022. To get a better understanding of the annual situation the study period should be extended to cover at least a complete growing season, but preferably several years to allow for unusual weather patterns or biotic events to be captured.

The CO_2 leak within the monitoring shed and the multi-port sampler have now been fixed.

The installation of the CO_2 analyser in the Flux lab, monitoring the CO_2 concentration above the woodland (at 50m high) is providing valuable background data to the wider FACE experiment.

It is important when setting up a FACE experiment to be aware of the proximity of the spaces and the relationship to the direction of the prevailing wind. This research adds an extra dimension to this, showing that although the spaces at BIFoR are relatively close they were mostly unaffected by the eCO_2 spaces. This monitoring system could be utilised in other spaces of the forest, for example downwind of the eCO_2 spaces to determine how far the enhancement overspill migrates. The design and programming of this monitoring system is now freely available for other FACE experiments to use in their undisturbed spaces or other areas of the BIFoR forest.

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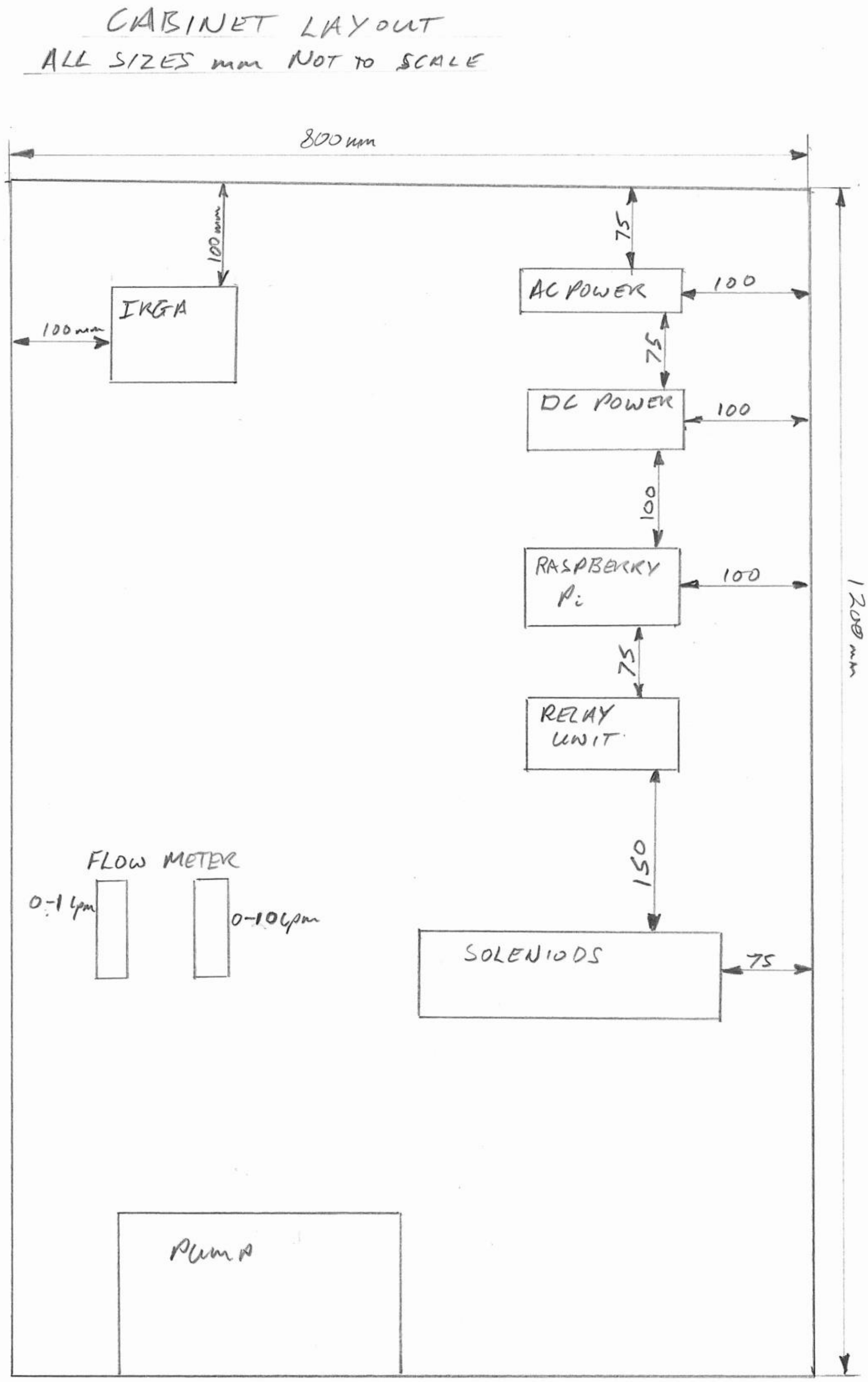
7. APPENDICES

7.1. Appendix A

Cabinet Schematic Drawing



CABINET LAYOUT
ALL SIZES mm NOT TO SCALE
800 mm
100 mm
IRGA
100 mm
75
AC POWER
100
75
DC POWER
100
100
RASPBERRY Pi
100
75
RELAY UNIT
1200 mm
150
FLOW METER
0-1 lpm
0-10 lpm
SOLENIODS
75
PUMP

7.2. Appendix B

The Python program an example from Undisturbed Area 7

This program is available to download from;

https://github.com/NickBIFoR/uCO2Monitoring/blob/main/Ghost_MPReadW_D2.py

```
/usr/bin/env python
from array import *
import time
import os
from datetime import datetime
import serial
import RPi.GPIO as GPIO
GPIO.setmode(GPIO.BCM)
GPIO.setup(4,GPIO.IN)
GPIO.setup(1,GPIO.OUT)
GPIO.setup(5,GPIO.OUT)
GPIO.setup(16,GPIO.OUT)
GPIO.setup(24,GPIO.OUT)
GPIO.setup(25,GPIO.OUT)
celltemp=0
cellpress=0
cellCO2="empty"
cellCO2abs=0
Pcount=0
purge=10
Rcount=1
read=20
Portcount=1
port=5
BadRead = 0
Grab=[0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
IN_list = [0,3,8,4,5,7]
LY_list = [0,6,1,5,4,2]
Z_list =[ 0,21,0.2,18,15,2]
# AvrGrab is worked on 20 grabs -- check code if you change number of Grab
```

```
AvrGrab=0
# Added Plot number
Plot= ('7')
Plottxt=('MP7-')
Fdate = 0
ser = serial.Serial(
    port='/dev/ttyUSB0',
    baudrate=9600,
)
# Send purge values to screen not file
# Port 1 now wired N/C
while ser.isOpen():
        while Portcount < (port+1):
        if Portcount == 1:
            GPIO.output(1,GPIO.LOW)
            GPIO.output(5,GPIO.LOW)
            GPIO.output(16,GPIO.LOW)
            GPIO.output(24,GPIO.LOW)
            GPIO.output(25,GPIO.LOW)
        elif Portcount == 2:
            GPIO.output(1,GPIO.HIGH)
            GPIO.output(5,GPIO.HIGH)
            GPIO.output(16,GPIO.LOW)
            GPIO.output(24,GPIO.LOW)
            GPIO.output(25,GPIO.LOW)
        elif Portcount == 3:
             GPIO.output(1,GPIO.HIGH)
             GPIO.output(5,GPIO.LOW)
             GPIO.output(16,GPIO.HIGH)
             GPIO.output(24,GPIO.LOW)
             GPIO.output(25,GPIO.LOW)
        elif Portcount == 4:
```

```
    GPIO.output(1,GPIO.HIGH)
    GPIO.output(5,GPIO.LOW)
    GPIO.output(16,GPIO.LOW)
    GPIO.output(24,GPIO.HIGH)
    GPIO.output(25,GPIO.LOW)
elif Portcount == 5:
    GPIO.output(1,GPIO.HIGH)
    GPIO.output(5,GPIO.LOW)
    GPIO.output(16,GPIO.LOW)
    GPIO.output(24,GPIO.LOW)
    GPIO.output(25,GPIO.HIGH)
while Pcount < purge:
    Rcount=0
    time.sleep(0.800)
    datastring = ser.readline()
    'print (datastring)'
    # celltemp=datastring[23:32]
    # cellpress=datastring[53:62]
    cellCO2=datastring[78:87]
    # cellCO2abs=datastring[101:113]
    print('Port ' + str(Portcount) + ' Purge ' + str(Pcount)+' ' + str(cellCO2))
    Pcount = Pcount + 1
  # Write to grab each scan -- scan 1 sec
while Rcount < read:
    Pcount = 0
    time.sleep(0.800)
    datastring = ser.readline()
  # Use as debugging print entire string
  # 'print (datastring)'
  #  f=open("/home/pi/7GHOST_SHARE/RAW7-"+ Fdate +".txt", "a+")
   # print Header ??
   # print ( " Plot, Date, Time, Port, CMP, G0 .. G19")
```

```
  #  f.write ( str(datetime.now())+' ' + str(datastring))
  #  f.close()
   # celltemp=datastring[23:32]
   # cellpress=datastring[53:62]
   cellCO2=datastring[78:87]
   # cellCO2abs=datastring[101:113]
   if ">" in str(cellCO2):
       BadRead = BadRead + 1
       # Grab[Rcount] = Grab[Rcount -1]
       print('BadRead', str(BadRead))
   elif  "<" in str(cellCO2):
       BadRead = BadRead + 1
       # Grab[Rcount] = Grab[Rcount -1]
       print('BadRead', str(BadRead))
   elif  "/" in str(cellCO2):
       BadRead = BadRead + 1
       # Grab[Rcount] = Grab[Rcount -1]
       print('BadRead', str(BadRead))
   else:
       Grab[Rcount] = cellCO2
       AvrGrab = AvrGrab + float(Grab[Rcount])
   print('Port ' + str(Portcount)+' Grab '+ str(Rcount) + ' ' + str(Grab[Rcount]) +' Summ '
+ str(AvrGrab) )
  Rcount = Rcount + 1
  # Write file only once
  # print(( Plot , datetime.now(),'CellTemp', celltemp, 'Press', cellpress, 'CO2', cellCO2))
  # print(Grab[0],Grab[1])
  # print( Grab, end= " ")  This will print entire array but adds []
  # Average 20 off values from grab change this number will change if read number
change  s
  # Average is calculated G0-G19 as 19 < 20 but there are 20 values
AvrGrab = AvrGrab / (read )
print( 'CMP Average ' + str(AvrGrab))
```

```
        Fdate = (time.strftime("%Y%m%d"))

        Rdate = (time.strftime("%Y/%m/%d"))

        Rtime = (time.strftime("%H:%M:%S"))

        f=open("/home/pi/"+Plot+"GHOST_SHARE/MP"+Plot+"-"+ Fdate +".CSV", "a")

        # Jan 22 if os.stat("/home/pi/"+Plot+"GHOST_SHARE/MP"+Plot+"-"+ Fdate
+".CSV").st_size == 0:

            # print Header ??

            # print ( " P, DATE, TIME, Port, CMP, G0 .. G19")

        # Jan 22   f.write( "P, DATE, TIME, SOLALT, T, F,
D,IN,LY,X,Y,Z,TP,TS,WS,WD,FLOW,CSET,CF,CMP,HMP,G1,G2,G3,G4,G5,G6,G7,G8,
G9,G10,G11,G12,G13,G14,G15,G16,G17,G18,G19,G20\n")


        f.write ( str(Plot)+','+ str(Rdate)+','+str(Rtime)+',,,,,'+ str(IN_list[Portcount])+','
+str(LY_list[Portcount])+',,,' +str(Z_list[Portcount])+',,,,,,,,'+str(AvrGrab)
+',,'+str(Grab[0])+',' + str(Grab[1])+','+ str(Grab[2])+','+ str(Grab[3])+','+ str(Grab[4])+','+
str(Grab[5])+','+ str(Grab[6])+','+ str(Grab[7])+','+ str(Grab[8])+','+ str(Grab[9])+','+
str(Grab[10])+','+ str(Grab[11])+','+ str(Grab[12])+','+ str(Grab[13])+','+ str(Grab[14])+','+
str(Grab[15])+','+ str(Grab[16])+','+ str(Grab[17])+','+ str(Grab[18])+','+ str(Grab[19])+"\n" )

        f.close()

        AvrGrab = 0

        Portcount = Portcount +1

    Portcount = 1

ser.close()
```