Evaluating the potential of glasshouse CO^2 enrichment to mitigate heating emissions in protected crops

About the author:

At the time of writing, I am employed as Lead Glasshouse Strawberry Grower for The Summer Berry Company in West Sussex. Over the course of my career I have seen CO^2 become regarded as a ‘controversial’ input, due to its widely acknowledged performance-enhancing effects on crops but also its high cost, potential environmental effects and seemingly intangible nature within a crop. This study has allowed me to analyse high quality literature and become better informed about the nature of CO^2 generation, use and dynamics within protected cropping. Furthermore, by analysing data from my own glasshouse operation, I have gained valuable insights and feel I will now be able to manage CO^2 enrichment in a manner which is more efficient, both environmentally and agronomically.

- Jed Knaggs

Executive summary:

- Accounting for 66% of heating-related emissions from agriculture, heating sources and subsequent emissions within protected cropping will be an important part of the industry’s overall goal for reaching net-zero emissions.
- Many UK glasshouse growers capture and utilise the CO^2 resulting from the heating process, in order to enrich the aerial environment of their crops, leading to well documented increases in crop performance.
- However, it is not clear if this potential utilisation and uptake of CO^2 as a by-product of heating can be factored into a grower’s carbon footprint. Therefore, this essay aims to review the potential for CO^2 enrichment to mitigate glasshouse heating emissions or even act as a form of carbon capture and utilisation.
- By applying findings from the literature review combined with a year’s worth of hourly glasshouse climate data, provided by The Summer Berry Company UK, CO^2 uptake was calculated as 12.58% of the total dosed.
- Whilst a small proportion of the total dosage, when scaled up this represents 19.77 tonnes/ha and could therefore be treated as a significant reduction to a grower’s heating emissions and overall carbon footprint. Furthermore, crops with higher biomass and often lower rates of ventilation could show vastly improved uptake and therefore greater potential for mitigating heating emissions from protected horticulture.

Background and introduction:

As an essential component of photosynthesis, plants rely on carbon dioxide (CO^2) to facilitate optimum growth and photosynthetic rate, leading many growers of protected crops to 'enrich' the atmosphere within their facilities with CO^2 often up tothree times the ambient concentration (Adams, 2012). The effects of such enrichment are well documented in commercially important glasshouse crops, with yield increases reported at up to 62% in strawberries (Bushway et al 2002), 20-30% in tomatoes (Resh, 2013) and 24.7% in lettuce (Singh et al, 2020).

However, whilst valuable as an input within cropping systems, CO^2 in recent years surpassed 400ppm in the atmosphere, causing anthropogenic climate change, environmental stochasticity and endangering both biodiversity and human food supplies (Jones, 2017). Whilst efforts must be made to curb emissions of such atmospheric pollutants, this alone is not enough and focus must also be made on removing and storing carbon dioxide from the atmosphere, of which 2,000 gigatons have been added since the industrial revolution (Mulligan et al, 2020). In response to such an evident threat, the UK's farming industry has set a target of achieving net-zero emissions by 2040 (NFU, 2019), ten years earlier than the UK's Governments legally binding target for all industries (Garvey et al, 2021).

The UK protected cropping sector has been identified as an area of improvement in terms of emissions. Especially so with regards to heating, as protected cropping accounts for 66% of all heating-based energy demand across all sectors of UK agriculture (Warwick HRI, 2007). Whilst the overall environmental footprint of the horticultural sector remains small in comparison to other agricultural sectors, efforts have been made to regulate such emissions with policies such as the governmental Climate Change Levy (Lillywhite et al, 2007). However, despite the emissions occurred in heating protected crops, this CO^2 is often utilised as a by-product by growers to form CO^2 enrichment. This is achieved using CO^2 as a by-product of various heating sources such as combined heat and power (CHP) units and conventional boilers, although often with the addition of commercially sourced liquefied pure CO^2 gas (Dodd et al, 2018). Furthermore, renewable sources of heating are also growing in interest with biomass also being able to provide more environmentally efficient heating as well as a source of CO^2 enrichment (Oreggioni et al, 2019).

However, despite the utilisation of CO^2 as a by-product of heating, little work has been done to assess the significance of uptake associated with glasshouse crops and the potential for this figure to be deducted from a grower's carbon footprint. Therefore, this essay aims to review the most relevant research regarding CO^2 uptake by glasshouse crops and apply the findings to a real-life cropping scenario. This will then discuss whether CO^2 uptake can mitigate emissions from heating protected crops or even act as a form carbon utilisation, both of which would contribute to the industry's overall aims of achieving net-zero.

Literature review:

Current industry CO^2 demand and usage

An overview of the current CO^2 demand for the UK glasshouse industry has been analysed by Alberici et al (2017) on behalf of Imperial College London. This shows current demand for CO^2 to be approximately 60 ktCO^2/year for all sources, not distinguishing between commercially sourced CO2 and gases resulting from flue emissions. This cites tomatoes, cucumbers and aubergines as particularly capable crops with regards to utilising CO^2, with glasshouse tomato operations being typically enriched with dosage of up to 200kg/ha/hour. However, as CO^2 for enrichment can be created on-site or commercially procured, it is possible that, depending on the source, externally supplied CO^2 could even act as a form of carbon capture and utilisation (CCU).

Carbon capture and utilization:

Carbon capture and utilization represents a significant opportunity for what Marchi et al (2018) describe as industrial symbiosis, a mutually beneficial relationship between energy-intensive industrial processes and glasshouse/protected horticulture. Here the authors give an extensive analysis of the agronomic and commercial possibilities that could result from the coupling of large-scale glasshouse growing systems with industrial manufacturing, by comparing tomato, cucumber and strawberry crops grown and concluding potential economic benefits between 0.68 – 1.6 M€/year for a 10 hectare site. Here such economic returns were maximised in cucumber growing, followed by tomatoes and then strawberries, citing the generally lower yield returns resulting from CO^2 enrichment of strawberries in comparison to the other two aforementioned crops. Furthermore, here it is also cited that not only does CO^2 enrichment boost crop performance in terms of yields and economic returns, European protected horticulture alone could save 22 million tonnes of CO^2 annually as a result of enrichment. However, such assertions simplify the dynamic of CO^2 enrichment and the ultimate net benefits in terms of total carbon capture depend on a more complex interaction between plants, CO^2 uptake and glasshouse management.

Dynamics of CO^2 within protected cropping structures

As a crucial technique in managing glasshouse temperature and humidity, it is likely that growers will choose to ventilate their structures therefore incurring losses of inputted CO^2 and creating complexity in identifying how much carbon is utilised via crop uptake, versus how much may be leaked to the outside atmosphere. It is with this in mind that Effat et al (2015) have claimed that 'ventilated greenhouses cannot be considered in carbon capture and utilization.' Mathematical modelling suggested crops within ventilated glasshouses (with an unstated degree of ventilation) will uptake CO^2 up to 52 times less than in an entirely closed structure. In this study, which used tomatoes and cucumbers as representative crops, it was found that tomato plants have the greatest potential for uptake of the glasshouse crops studied, with an uptake of up to 140g/m^2/day, compared to 120g/m2/day for cucumbers. Furthermore, this performance is heavily influenced by the plant structure and foliar density. An increase in Leaf Area Index (LAI) in cucumbers from LAI 1 to LAI 3 increased uptake from approximately 50g/m^2/day to the maximum recorded during the study of 120g/m^2/day. However, whilst larger foliar areas would increase uptake, they would also lead to a greater relative humidity due to the increased area of transpiration, therefore significant increases in volume of CO^2 needed would be likely due to the greater uptake and increased likelihood of ventilation being necessary to maintain an optimum climate. Overall, it seems overly-simplistic to dismiss ventilated growing systems as incapable of CCU. After all, if there was indeed no capture and utilization from the plants, there would be no agronomic benefit and therefore it is unlikely growers would use such economically costly practices if ineffective. Therefore, a system to calculate actual usage based on constantly changing ventilation and glasshouse management practices is needed.

One such system has been created by Van den Berg et al (1999) on behalf of Wageningen University, Netherlands. Here, researchers have created a formulaic process to establish the ventilation loss of CO^2 in a glasshouse environment. The equation used can be summarised as such:

CO^2 Ventilation loss = Ventilation rate x Average greenhouse height x CO^2 difference x 0.0018

Here 'CO^2 difference' is the difference between outside and inside CO^2 concentrations and ventilation rate = 0.09 x wind speed (m/s) x (the ventilation percentage opening + leakage). Furthermore, leakage is an estimated figure between 0.3 and 2 depending on age of the glasshouse. This system offers a more precise way of calculating ventilation losses in comparison to previous research which rules out the possible carbon utilisation from vented glasshouses and could therefore be used to calculate carbon uptake by the subtracting the amount of CO^2 lost from the total CO^2 input.

Discussion:

Case study: Glasshouse cropping

As the literature cited above suggests, it is clear that there is a varying level of uptakes by crop depending on not only individual crop physiology but the growing environment and climatic factors. Using Van den Berg et al's (1999) system, it is possible to deduce how much CO^2 is lost due to ventilation and air exchange within the glasshouse environment. Once calculated, this figure of losses could be deducted from the total input figure, with the remaining sum presumably being utilised by the crop. The following data has been provided by The Summer Berry Company UK (with permission) and gives an example of such a calculation using an example of a commercial 2.6 hectare strawberry-growing glasshouse, for the entire 2020 year, covering two crops (Spring and Autumn). Using the full data set of growing conditions downloaded from the Priva climate computer (Priva, The Netherlands) (a sample of which is displayed in appendix 1), hourly climate data for 2020 has been analysed. The results of which are displayed in Table 1, on the following page.

	Ventilation loss		Dosage	
	g/m^2	T/ha	g/m^2	t/ha
January	38.67	0.39	1178.83	11.79
February	147.51	1.48	924.97	9.25
March	2270.07	22.70	2665.43	26.65
April	4856.33	48.56	3051.42	30.51
May	2174.86	21.75	1349.61	13.50
June	0.00	0.00	0.00	0.00
July	0.00	0.00	0.00	0.00
August	631.21	6.31	804.76	8.05
September	2071.28	20.71	1675.33	16.75
October	1267.73	12.68	2270.44	22.70
November	286.83	2.87	1733.88	17.34
December	2.37	0.02	69.71	0.70
Total:	13746.86	137.47	15724.38	157.24

Table 1: Ventilation losses and dosage rates for a UK glasshouse strawberry crop

This was calculated using in an East-West orientated glasshouse, of approximately 3.55M height, with an estimated rate of leakage of 0.8 (an estimation based on age highlighted in Van den Berg et al's (1999) research) and assumed an outside CO^2 concentration of 400ppm as suggested by Jones (2017).

From this data it seems total dosage for 2020 totals 15724.38g/m^2 compared to a vent loss of 13746.86/m^2 during dosage. This difference of 1,977.52/m^2 therefore can represent uptake by the crop. This data, which compares ventilation losses only during CO^2 dosage to avoid respiration/background losses or influences, shows ventilation losses of 87.42% leaving 12.58% of CO^2 as potentially utilised by the crop. This therefore reinforces hypotheses previously mentioned which suggest ventilated glasshouses are not efficient methods of carbon capture and utilization. On the other hand however, this proportionately small 12.58% uptake when scaled up shows that a substantial amount is still taken up by the crop. For example, on a per-hectare basis this represents an uptake of 19.77 tonnes, totalling 51.4 tonnes being sequestered by the crop during the entire year in this particular example.

However, it does seem that there are anomalies within this data set, particularly in April, May and September where the dosage is less than the calculated ventilation losses. However, due to the nature of the calculation there are some ventilation losses occurring without dosage. For example, in June and July, when there was zero CO^2 dosage, there were still ventilation losses of 1,573.95g/m^2 indicating there could be some background rate (such as plant respiration and pre-existing concentration differences) causing additional losses. Furthermore, there are additional climatic factors that should potentially be included when calculating CO^2 ventilation loss which are not currently accounted for within this formula. For example the width of the vents themselves, the wind direction and glasshouse orientation amongst other factors should also be considered during this calculation. In addition to these abiotic factors, previously mentioned physiological differences within cropping such as leaf area and overall biomass will also affect uptake and therefore the potential validity of this calculation.

Nonetheless, if we replace the anomalies in April, May and September with a 95% ventilation loss to assume/estimate a reasonable 'worst case scenario', inputted CO^2 uptake can be viewed as follows throughout the year:

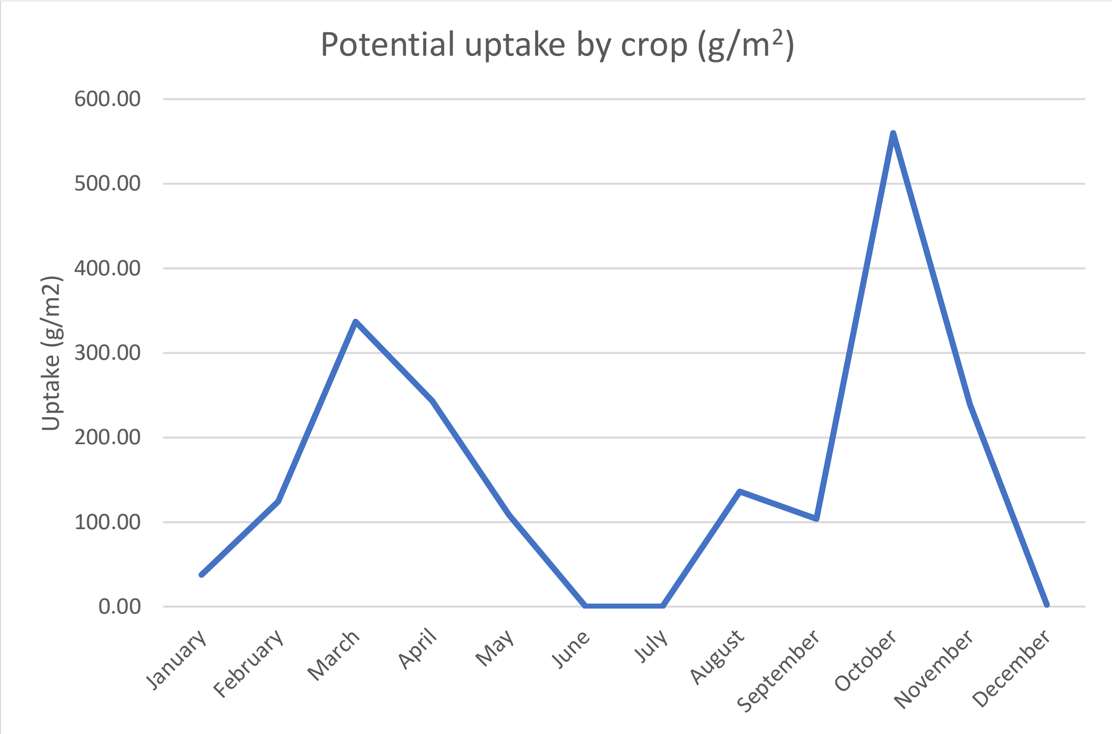

Figure 1: Potential uptake by crop (g/m²)

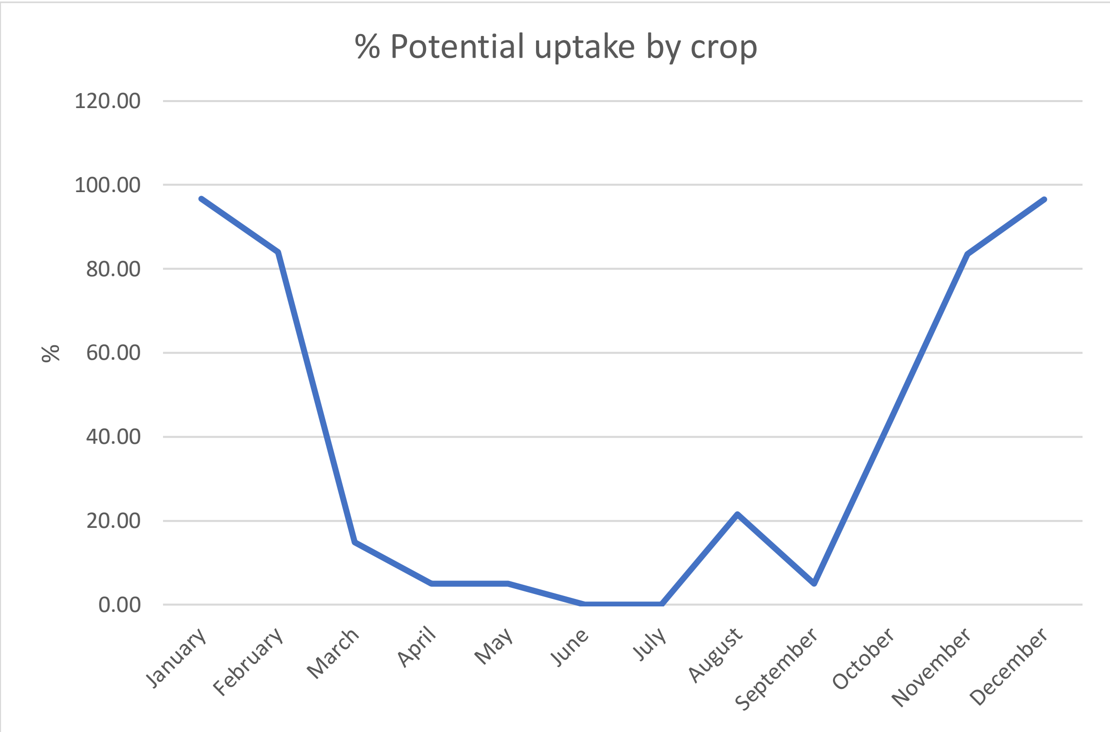

Figure 2: % Potential uptake by crop

This shows CO^2 uptake to be greater in typically cooler months when it is likely that a lower ventilation rate is needed to cool the crop. This could indicate that a crops potential to effectively uptake carbon could be both seasonal and weather-dependent due to the effect of venting. This is illustrated in Figure 2, displaying the inevitable positive correlation between ventilation rates and ventilation losses, largely incurred due to the need to cool the glasshouse.

	Ventilation rate	Ventilation loss
	%	T/ha
January	0.4	0.39
February	0.3	1.48
March	3.5	22.70
April	21.7	48.56
May	11.2	21.75
June	0.0	0.00
July	0.0	0.00
August	6.8	6.31
September	17.4	20.71
October	5.8	12.68
November	1.9	2.87
December	0.0	0.02

Table 2: Ventilation rate (%) and loss (T/ha)

Nonetheless, the data displayed in Table 1 shows that there is potential for some, albeit proportionally small, CO^2 uptake even from heavily ventilated crops, previously described as incapable of contributing significant carbon capture. However, this figure for CO^2 uptake could be dramatically improved in crops with a physiological advantage (due to larger biomass) as well as less ventilated growing conditions, such as tomatoes and cucumbers. In the literature review above, Effat et al (2015) suggested that uptake in a closed environment can increase by 52-fold in comparison with ventilated crops and therefore this finding combined with the data above shows a vast potential for carbon capture from other commercial glasshouse crops. Furthermore, this same study recorded glasshouse cucumber and tomato crops achieving an uptake of 120 to 140g/m^2/day, suggesting a potential uptake of 1.2-1.4t/ha/day respectively. Such a large figure shows the potential scale of previously unacknowledged uptake and under such conditions could even enable effective carbon capture and utilisation.

Therefore, it is recommended the calculation of ventilation loss proposed by Van den Berg et al (1999) be developed in conjunction with similar climate data from commercially significant glasshouse crops to identify a potentially large and previously unacknowledged amount of carbon utilization.

Using this data

With regards to using this calculation, if refined in order to achieve an acceptable level of accuracy, this figure from uptake could be deducted from a grower's total carbon footprint, subsequently contributing towards the industry's aims of achieving net-zero.

However, it is also necessary to distinguish between the type of dosage in relation to its source. If the CO^2 being dosed is a result of using a heating system, then it is likely that the uptake of this CO^2 could be deducted from the overall emissions from heating. On the other hand, commercially sourced CO^2, if resulting from industrial processes, would be more eligible to be considered carbon capture and utilisation as it does not result from a grower's actions and instead is reducing emissions of other industrial activities. Whilst using such CO^2 does fit into CCU framework proposed by Marchi et al (2018), any externally sourced gases would also need to be examined for their upstream emissions facilitating this supply, such as storage and transportation prior to dosage as well as any other emissions incurred during the dosage process. However, due to the proportionally low rate of CO^2 uptake it is clear any carbon capture would only be partial in the cropping scenario given and therefore may not be considered as an efficient form of carbon capture.

However, as Figure 2 suggests, the percentage of uptake is maximised during cooler months. This is significant in relation to the CO^2 source as it is likely these cooler months will see more intensive use of heating facilities and therefore a greater proportion of CO^2 dosed in these periods is likely to arise from this heating. Therefore, commercially sourced CO^2 is likely to be used when heating demand is less intense, typically at times of lower uptake efficiency, in hotter conditions, when ventilation rate is likely to be higher. This will subsequently reduce the likelihood of effective CCU, unless crop CO^2 demand exceeds that of what is available due to heating.

Overall, it is hoped that these findings will not be used as a low-effort method for growers to lower their carbon footprint or dis-incentivise organisations from investing in more renewable heating sources. Rather, by refining a method for accurately calculating ventilation losses and crop uptake, it would be possible for growers to be able to manipulate the glasshouse environment so as to maximise possible uptake and reduce ventilation losses, therefore increasing the proportion of CO^2 gases which are then utilised by the crop rather than being lost as heating emissions. For example, Table 3 shows recalculated data for ventilation losses displayed in Table 1, with various reductions in ventilation rates and subsequently lower ventilation losses.

			Decrease to average ventilation rate							
	No decrease		10%		20%		50%		Dosage	
	g/m^2	T/ha	g/m^2	T/ha	g/m^2	T/ha	g/m^2	T/ha	g/m^2	t/ha
January	38.7	0.4	34.8	0.3	30.9	0.3	19.3	0.2	1178.8	11.8
February	147.5	1.5	132.8	1.3	118.0	1.2	73.8	0.7	925.0	9.2
March	2270.1	22.7	2043.1	20.4	1816.1	18.2	1135.0	11.4	2665.4	26.7
April	4856.3	48.6	4370.7	43.7	3885.1	38.9	2428.2	24.3	3051.4	30.5
May	2174.9	21.7	1957.4	19.6	1739.9	17.4	1087.4	10.9	1349.6	13.5
June	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
July	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
August	631.2	6.3	568.1	5.7	505.0	5.0	315.6	3.2	804.8	8.0
September	2071.3	20.7	1864.2	18.6	1657.0	16.6	1035.6	10.4	1675.3	16.8
October	1267.7	12.7	1141.0	11.4	1014.2	10.1	633.9	6.3	2270.4	22.7
November	286.8	2.9	258.1	2.6	229.5	2.3	143.4	1.4	1733.9	17.3
December	2.4	0.0	2.1	0.0	1.9	0.0	1.2	0.0	69.7	0.7
Total:	13746.9	137.5	12372.2	123.7	10997.5	110.0	6873.4	68.7	15724.4	157.2

Table 3: Uptake simulation under different ventilation rates

Here, fairly gradual and realistic decreases to the ventilation rate of 10% and 20% have been simulated as well as a reduction of 50% which may be unrealistic within this case study but more applicable in higher temperature crops. This shows a 10% reduction in venting led to a reduction in ventilation losses of 14.5T/ha (10.54%) and a 27.5t/ha reduction at 20% lower ventilation rate (20%). This linear relationship between ventilation rate and losses could therefore allow growers to enhance CO^2 uptake through a more cautious approach to venting based on less ventilation if possible or reduced dosing during periods of high ventilation. If such calculations were developed and made available to growers in an accessible and accurate manner, it would enable a cost-effective and additional method of reducing emissions and therefore contribute to the industry's overall goal of net-zero emissions.

Conclusion

With the UK's ambitious plans to achieve net-zero emissions from all agricultural sectors, horticulture must play its part in curbing and - where possible – removing CO^2 from the atmosphere. The most notable emissions from this sector occur within protected cropping, with the majority being associated with heating.

Protected crop growers in the UK and elsewhere often utilise CO^2 emissions from heating their structures to provide CO^2 enrichment with well documented increases to agronomic and commercial performance. However, the amount which could be utilised by the crop, and therefore deducted from the overall carbon footprint of the grower is rarely considered.

Academic studies into carbon uptake of various glasshouse crops conclude that whilst there is significant uptake from crops, up to 140g/m^2/day in some cases, there are also significant losses from ventilation. Whilst this has led to ventilated structures being condemned as unsuitable for carbon capture by some researchers, other research into quantifying ventilation losses suggest there is some potential for uptake even in heavily ventilated environments. Analysis using calculations of ventilation losses combined with hourly climate and dosage data from a glasshouse strawberry operation in West Sussex, England, show that even ventilated crops can have a significant uptake. Here it was found that a modest 12.58% of dosed CO^2, whilst proportionately small, equates to almost 20 tonnes/ha of CO^2 uptake when scaled up.

It is therefore hypothesised that this figure could be deducted from the grower's carbon footprint/heating emissions. Whilst CO^2 being dosed and used as a result of heating could be recorded as a deduction to the overall heating emissions, it is possible that externally sourced CO^2 could be utilised as a form of carbon capture and utilisation. However, it is acknowledged that the rate of uptake versus dosage would have to be greatly improved to represent full carbon 'capture.' Nonetheless, it seems possible that quantifying a crops CO^2 uptake from enrichment could contribute to the industry's goal of achieving net-zero.

References

- Adams, C.R. Bamford, K.M. Early, M.P. Principles of Horticulture. Sixth Edition. Routledge. England. Page 94. (Accessed 25/03/2021)
- Alberici, S. Noothout, P. Mir, G.U.R. Stork, M. Wiersma, F. Dowell, N.M. Shah, N. Fennell, P. 2017. ASSESSING THE POTENTIAL OF CO2 UTILISATION IN THE UK. Pages 50-55. Online resource available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/799293/SISUK17099AssessingCO2_utilisationUK_ReportFinal_260517v2__1_.pdf (Accessed 27/03/2021)
- Bushway, L.J. Pritts, M.P. 2002. Enhancng Early Spring Microclimate to Increase Carbon Resources and Productivity in June-bearing Strawberry. Online journal available at: https://journals.ashs.org/jashs/view/journals/jashs/127/3/article-p415.xml (Accessed 26/03/2021)
- Dodd, I. 2018. Increasing crop yield and resource use efficiency via root-zone CO2 enrichment. Online journal available at: https://projectblue.blob.core.windows.net/media/Default/Research%20Papers/Horticulture/CP143_GS_Report_Final_2018.pdf (Accessed 10/04/2021)
- Effat, M.B. Shafey, H.M. Nassib, A.M. Solar greenhouse can be promising candidate for CO2 capture and utilization: mathematical modelling. 2015. Online journal available at: https://link.springer.com/article/10.1007/s40095-015-0175-z (Accessed 18/03/2021)
- Garvey, A. Norman, J.B. Owen, A. Barrett, J. 2021 Towards net zero nutrition: The contribution of demand-side change to mitigating UK food emissions. Online journal available at: https://www.sciencedirect.com/science/article/pii/S0959652620357188
- Jones, N. 2017. How the World passed a Carbon Threshold and Why it Matters. Online report available at: https://e360.yale.edu/features/how-the-world-passed-a-carbon-threshold-400ppm-and-why-it-matters (Accessed 25/03/2021)
- Lillywhite, R. Chandler, D. Grant, W. Lewis, K. Firth, C. Schmutz, U. Halpin, D. Environmental Footprint and Sustainability of Horticulture (including Potatoes) – A Comparison with other Agricultural Sectors. Online report available at: http://randd.defra.gov.uk/Document.aspx?Document=WQ0101_6748_FRA.pdf (Accessed 03/04/2021)
- Marchi, B. Zanoni, S. Passetti, M. 2018. Industrial symbiosis for greener horticulture practices: the CO2 enrichment from energy intensive industrial processes. Online journal available at: https://pdf.sciencedirectassets.com/282173/1-s2.0-S2212827118X00043/1-s2.0-S2212827117309022/main.pdf?X-Amz-Security-Token=IQoJb3JpZ2luX2VjEOz%2F%2F%2F%2F%2F%2F%2F%2F%2F%2FwEaCXVzLWVhc3QtMSJHMEUCIQCrHOWFZoaBeSK3AlvAVxo1eg9MuM2IHws%2BCh56Zrt1AQIgT4WhQh9VMvQc6aaBzbB8zh5Sv7%2ButkLcePf8g3SwlSoqtAMIZRADGgwwNTkwMDM1NDY4NjUiDF7L9SjCxdvLWt795CqRA%2F8XHeJtmx5lVGVR0gYbvzIJw1t3%2FKmw4xuwhP%2Fee9dV%2Fy%2BuizwnsGLn0GTNm055vGklc1xQXoDkMk0joFkLfPQj4T8MzXFLH1IkHdJAiZN%2FI76wQoM4PB2TxoRooJnV0Qy3%2Bb5CiGZWF23IdIvpzvT79BnJm%2BnqZCCxWNxqS0YutuMV4deE%2B07p7yNAaeEmdfrEYbKFDyVFU02wGql9jZCV

FY1qVieC66J8IrwWywqBy3EJUVs5uv%2FvJtIneErv%2BHw0SddFnMfDHlCOqT39Kywz%2Bk7b%2BkkN4bun0lMQvXQ6stgZPC%2FUAvP5tEezVlm9GMbi3mfOwQx93ERsO4YT8oWOYifRv8ishMITpMpNrUwtDVQ%2BEFBOPrcVS6TQrqrNX0eDBmif9NJ4AOmfiFsRueNHa9BjBMg%2Fb7qkIluYSgNOFqDCxqzygGKMW6Jzq5hWnJVvL2G5hkgC2bEh6w%2ByNPwuT%2BJ0EtZkPWqerJppGuEMjXbO3wFCuZ482pmTND8i8IfaEwaLJNEIORuqIpMolnMNMKzupoQGOusBgWzNqvKXg00l1%2FgeIWeI%2Blfd1PCa80TOtnmk7dJBeYkA0rfSFQZbqINhiPWDa%2FmBREDTNHB4g4WZLIvJ%2BgL%2F7u669xfcnVG6xoDAkolE6or%2F3xwcFH4lwfG2J92%2F9IXknBdtlIYNVA7ek44l9MrSyjv%2Ba1rXvvJErMeCrhHNQC9n%2B5oRB0SVUUEVQwS5PpWamn%2BFFDSkbqHs7HuMAIHVBWOiA5V%2FmPjhdelJN2DmHVkYf7q87XzPwzb7djWA%2F%2FKTaZ%2FUIzt8aHZTiXbxb6r0sdztuQ8WFm%2BUIcvFPevxvO21XI1aEq%2FxfZoGkg%3D%3D&X-Amz-Algorithm=AWS4-HMAC-SHA256&X-Amz-Date=20210428T200043Z&X-Amz-SignedHeaders=host&X-Amz-Expires=300&X-Amz-Credential=ASIAQ3PHCVTYWA4P6FZ6%2F20210428%2Fus-east-1%2Fs3%2Faws4_request&X-Amz-Signature=0183dcea7b5fad8f61c9d27ac39a2517d3113f3e05f99055032c30dd3845388e&hash=ddacb3c5cb2e334aa012907db2ed30ea0ac96e391d23f2ff30b6c8fbdae306f4&host=68042c943591013ac2b2430a89b270f6af2c76d8dfd086a07176afe7c76c2c61&pii=S2212827117309022&tid=spdf-cc23f7a0-032d-444d-b812-11536d0b63e6&sid=e41465c741c766471098b9e26a60bb4f1bdagxrqb&type=client (Accessed 02/04/2021)

- Mulligan, J. Ellison, G. Leven, K. Lebling, K. Rudee, A. 2020. 6 Ways to Remove Carbon Pollution from the Sky. Online article available at: https://www.wri.org/insights/6-ways-remove-carbon-pollution-sky (Accessed 25/03/2021)
- NFU, 2019. Achieving Net Zero. Farming's 2040 Goal. Online report available at: https://www.nfuonline.com/nfu-online/business/regulation/achieving-net-zero-farmings-2040-goal/ (Accessed 26/03/2021)
- Oreggioni, D. Brandani, S. Luberti, M. Baykan, Y. Friedrich, D. Woong, H. CO_2 capture from syngas by an adsorption process at a biomass gasification CHP plant: Its comparison with amines-based CO_2 capture. Online journal available at: https://www.sciencedirect.com/science/article/pii/S1750583615000249 (Accessed 12/04/2021)
- Resh, H.M. 2013. Hydroponic Food Production. A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower SEVENTH EDITION. CRC Press. United States. Page 404. (Accessed 25/03/2021)
- Singh, H. Poudel, M.R. Dunn, B.L. Fontainer, C. Kakani, G. 2020. Effect of Greenhouse CO_2 Supplementation on Yield and Mineral Element Concentrations of Leafy Greens Grown Using Nutrient Film Technique. Online journal available at: res.mdpi.com › agronomy-10-00323-v2 (Accessed (25/03/2021)
- Van den Berg, G.A. Esmeijer, M.H, de Graaf, R. Nederhoff, E, Rijsdijk,A.A. Stapel-Cuypers, L.H.M. Vermuelen, P.C.M. Batta, L. Van Eijk, J. Van Gaaien, C. Latour, P.A.M. Lelie, J. Noordermeer, F. Ogink , R.A.M. Blokpoel, L. Van der Schans, R. Stijger, H.C.M. Verveer,J. Wijlens,J. (1999). CO_2 in

greenhouse horticulture. Wageningen University. Online resource available at: https://edepot.wur.nl/274827 (Accessed 03/04/2021)

- Warwick HRI, 2007. AC0401: Direct energy use in agriculture: opportunities for reducing fossil fuel inputs. Online report available at: https://ukerc.rl.ac.uk/pdf/AC0401_Final.pdf (Accessed 25/03/2021)

Appendix 1:

Below is a sample of two days of data collection used to calculate ventilation losses displayed in Table 1 and throughout.

	Meas CO2	CO2 dosage to	meas lee	Wind spe	meas win	meas radi	Av Vent	Av. Vent	Av vent minus x% Vent rate			CO2 diff	Vent loss during dosage (g/m2)			
	ppm	kg CO2/ha/hr	%	m/s	m/s	W/mÂ²	%	whilst dosing	10	20	50		Regular	10% dec.	20% dec.	50% dec.
05/01/2020 00:00	548.21	0	0	0.00	0	0	0	0	0	0	0	148.21	0	0	0	0
05/01/2020 01:00	535.36	0	0	0.88	0	0	0	0	0	0	0	135.36	0	0	0	0
05/01/2020 02:00	547.52	0	0	0.87	0	0	0	0	0	0	0	147.52	0	0	0	0
05/01/2020 03:00	570.45	0	0	0.44	0	0	0	0	0	0	0	170.45	0	0	0	0
05/01/2020 04:00	558.34	0	0	0.08	0	0	0	0	0	0	0	158.34	0	0	0	0
05/01/2020 05:00	563	0	0	0.71	0.21	0	0	0	0	0	0	163	0	0	0	0
05/01/2020 06:00	558.66	0	0	2.80	0.55	0	0	0	0	0	0	158.66	0	0	0	0
05/01/2020 07:00	583.06	0	0	0.81	0	0	0	0	0	0	0	183.06	0	0	0	0
05/01/2020 08:00	593	0	0	0.41	0	0.73	0	0	0	0	0	193	0	0	0	0
05/01/2020 09:00	517.76	88.04	0	0.90	0.66	9.72	0	0	0	0	0	117.76	0	0	0	0
05/01/2020 10:00	499.88	78	3	1.59	1.04	52.17	1.5	1.5	1.35	1.2	0.75	99.88	0.109666	0.0987	0.087733	0.054833
05/01/2020 11:00	462.39	133.18	7	1.27	1.33	85.66	3.5	3.5	3.15	2.8	1.75	62.39	0.127691	0.114922	0.102153	0.063846
05/01/2020 12:00	434.36	178.84	7	2.65	1.54	78.36	3.5	3.5	3.15	2.8	1.75	34.36	0.146678	0.13201	0.117342	0.073339
05/01/2020 13:00	422.35	229.81	7	3.25	1.53	69.39	3.5	3.5	3.15	2.8	1.75	22.35	0.117003	0.105302	0.093602	0.058501
05/01/2020 14:00	433.64	212.88	5	1.53	0.74	50.68	2.5	2.5	2.25	2	1.25	33.64	0.059239	0.053315	0.047391	0.029619
05/01/2020 15:00	428.83	174.92	3.77	1.36	0.28	28.77	1.885	1.885	1.6965	1.508	0.9425	28.83	0.034029	0.030626	0.027223	0.017014
05/01/2020 16:00	443.68	75	1.64	0.37	0	5	0.82	0.82	0.738	0.656	0.41	43.68	0.006114	0.005502	0.004891	0.003057
05/01/2020 17:00	466.52	0	0	0.57	0	0	0	0	0	0	0	66.52	0	0	0	0
05/01/2020 18:00	476.07	0	9.52	0.42	0	0	4.76	0	4.284	3.808	2.38	76.07	0	0	0	0
05/01/2020 19:00	440.8	0	12	0.00	0	0	6	0	5.4	4.8	3	40.8	0	0	0	0
05/01/2020 20:00	447.07	0	21	2.37	1.94	0	10.5	0	9.45	8.4	5.25	47.07	0	0	0	0
05/01/2020 21:00	414.54	0	21	2.29	2.66	0	10.5	0	9.45	8.4	5.25	14.54	0	0	0	0
05/01/2020 22:00	441.93	0	20	2.71	3.6	0	10	0	9	8	5	41.93	0	0	0	0
05/01/2020 23:00	428.19	0	12	3.08	2.22	0	6	0	5.4	4.8	3	28.19	0	0	0	0
06/01/2020 00:00	434.3	0	9	1.18	3.37	0	4.5	0	4.05	3.6	2.25	34.3	0	0	0	0
06/01/2020 01:00	445.85	0	0.93	2.72	2.19	0	0.465	0	0.4185	0.372	0.2325	45.85	0	0	0	0
06/01/2020 02:00	440.13	0	0	3.93	3.92	0	0	0	0	0	0	40.13	0	0	0	0
06/01/2020 03:00	455.8	0	0	2.32	2.77	0	0	0	0	0	0	55.8	0	0	0	0
06/01/2020 04:00	460.07	0	0	1.87	1.76	0	0	0	0	0	0	60.07	0	0	0	0
06/01/2020 05:00	462.8	0	0	2.85	3.02	0	0	0	0	0	0	62.8	0	0	0	0
06/01/2020 06:00	478.8	0	0	3.21	2.87	0	0	0	0	0	0	78.8	0	0	0	0
06/01/2020 07:00	492.51	0	0	3.29	2.53	0	0	0	0	0	0	92.51	0	0	0	0
06/01/2020 08:00	499.31	0	0	2.42	1.58	0	0	0	0	0	0	99.31	0	0	0	0
06/01/2020 09:00	506.67	159	0	3.90	3.98	23.67	0	0	0	0	0	106.67	0	0	0	0
06/01/2020 10:00	527.38	92.94	0	4.26	3.67	62.82	0	0	0	0	0	127.38	0	0	0	0
06/01/2020 11:00	460.23	152.97	4.39	3.71	4.16	71.84	2.195	2.195	1.9755	1.756	1.0975	60.23	0.225721	0.203149	0.180577	0.11286
06/01/2020 12:00	428.15	156	6	3.51	2.9	54.31	3	3	2.7	2.4	1.5	28.15	0.136416	0.122774	0.109132	0.068208
06/01/2020 13:00	429.9	204.68	6	3.04	3.35	66.58	3	3	2.7	2.4	1.5	29.9	0.1255	0.11295	0.1004	0.06275
06/01/2020 14:00	418.36	214	4.09	3.88	4.51	77.23	2.045	2.045	1.8405	1.636	1.0225	18.36	0.067041	0.060337	0.053633	0.033521
06/01/2020 15:00	411.36	176.44	2.2	2.27	2.41	3.48	1.1	1.1	0.99	0.88	0.55	11.36	0.013056	0.011751	0.010445	0.006528
06/01/2020 16:00	439.52	75	1	2.85	5.58	3.97	0.5	0.5	0.45	0.4	0.25	39.52	0.025919	0.023327	0.020735	0.012959
06/01/2020 17:00	453.53	0	0	4.02	3.81	0	0	0	0	0	0	53.53	0	0	0	0
06/01/2020 18:00	450.2	0	6.04	2.10	4.25	0	3.02	0	2.718	2.416	1.51	50.2	0	0	0	0
06/01/2020 19:00	424.95	0	29	3.08	2.01	0	14.5	0	13.05	11.6	7.25	24.95	0	0	0	0
06/01/2020 20:00	430.22	0	0	1.51	0.95	0	0	0	0	0	0	30.22	0	0	0	0
06/01/2020 21:00	442.57	0	0	0.39	0	0	0	0	0	0	0	42.57	0	0	0	0
06/01/2020 22:00	458.69	0	0	1.75	0	0	0	0	0	0	0	58.69	0	0	0	0
06/01/2020 23:00	467.42	0	0	1.93	0.24	0	0	0	0	0	0	67.42	0	0	0	0

Note, due to the vast amount of climate data analysed, totalling over 8,700 rows of data, a full data set has not been uploaded with this essay.