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A cost-effective system for injecting pure CO_2 into open top chambers: design and performance

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Abstract

Global average temperature is expected to rise between 0.2°C and 4.8°C by the end of the century, and globally atmospheric carbon dioxide concentration is expected to increase from a mean of 400 µmol mol^{-1} in 2013 to 550-650 µmol mol^{-1} within the next 50-80 years. Studies suggest there has already been an effect of warmer temperatures on grape growth and development, such as grape phenology, with harvest dates advancing and vintages becoming shorter over the past 30 years in Australia. Such changes create logistical problems for wineries and diminish grape quality. In addition, increasing carbon dioxide concentrations ([CO_2]) are likely to alter grape vine growth and development. Understanding the combined effect of elevated carbon dioxide concentration (e[CO_2]) and temperature together with their interactions on grape and wine qualities is necessary for industry adaption to future climate change. Therefore a system was developed to elevate [CO_2] to 650 µmol mol^{-1} and increase temperature by 2°C around the grapevines in open top chambers (OTC) to simulate climate warming. The temporal and spatial distribution of CO_2 gas at the center of the OTC was maintained to within 72 µmol mol^{-1} standard deviation of the target (650 µmol mol^{-1}), which is comparable to the distribution reported in Free Air CO_2 Enrichment (FACE) systems. The injection system described in this article consumed 60 g m^{-3} h^{-1} of CO_2 which is less than one-fifth of the CO_2 consumed by the Australian Grains Free Air CO_2 Enrichment system (318 g m^{-3} h^{-1}) and a circular OTC (316 g m^{-3} h^{-1}) used in a previous study as well as very similar to the consumption of the ForestFACE (50 g m^{-3} h^{-1}). The cost-effective CO_2 injection system proposed here is therefore recommended for use inside OTCs in evaluating the effects of e[CO_2] in combination with elevated temperature in woody perennial crops.

Keywords: **Grapevines, elevated CO_2, temperature, open top chamber, Australia.**

1 Introduction

Analyses of vintage records suggest that climate warming is already having an effect on the phenology of grapevines (*Vitis vinifera* L.), with harvest dates advancing by about eight days per decade over the last 30 years in Australia (Webb et al. 2011), with similar trends in Europe (Jones et al. 2005). The changes in global and local temperatures during the periods represented by these studies were small compared to the predictions made in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, which predicts global average temperature to rise between 0.3°C and 4.8°C by the end of the century, with >2°C being likely in the majority of emission scenarios considered (Rusticucci et al. 2013). The largest driver of this increase in temperature is atmospheric carbon dioxide concentration ([CO_2]), currently 401 µmol mol^{-1} (Scripps Institution of Oceanography 2014). For example, the A1B emission scenario of the IPCC Fourth Assessment Report predicts that [CO_2] will reach 550 µmol mol^{-1} by 2050 (Carter et al. 2007). Consequently, agronomical-agronomically important traits such as yield, water use efficiency, phenology and pest and disease incidence on crops are likely to be impacted by climate change (e.g. high CO_2 level) over the next 20 to 50 years.

It is possible to artificially elevate [CO_2] around growing plants using various methodologies. Open top chambers (OTCs) have often been used as one of the methods for conducting experiments with e[CO_2] in the field, particularly when studying woody perennial plants (e.g. Barton et al. 2010, Langley et al. 2013). Field based studies of the effects of elevated [CO_2] (e[CO_2]) on grapevines have been conducted (Bindi et al. 2001a, Gonçalves et al. 2009, Moutinho-Pereira 2009, Moutinho-Pereira 2010), but have been fairly short-term or limited in scope and are yet to be combined with control of temperature.

We have previously developed an OTC system (Edwards et al. 2012), using active heating, to elevate temperature around mature grapevines to study the effect of climate warming on grapevine development and grape quality parameters. Here, we describe the addition and testing of a prototype CO_2 injection system for use in OTCs (CO_2InOTC) to increase [CO_2] around the grapevines and compare the resource use and efficacy of our system with existing methodologies to study e[CO_2] effects in the field.

2 Materials and methods

System for injecting pure CO_2 into OTCs (CO_2InOTC)

In the CO_2InOTC system, pure CO_2 was injected (jets pointed downwards at 45º angle) into the atmosphere just below the canopy from both sides of the trellis, through 0.30 mm diameter holes at supply line pressures below 40 kPa. The intention of the design was for the CO_2 to quickly mix with the chamber air and be transported in and around the grapevines by air movement (with or without the heating system fan running).

A CO_2 sensor with relay facility (SEN51101S01, ETM Pacific Pty Ltd, North Sydney, NSW, Australia) was placed near the top shoot of the grapevine at the centre of the OTC and was used to switch the CO_2 supply on or off, using a solenoid valve, in order to maintain the target [CO_2] of 550 µmol mol^{-1}. Both the CO_2 sensor and the solenoid valve were powered by 24-V DC (direct current). The major components of the CO2InOTC system are shown in a schematic diagram (Fig. 1).

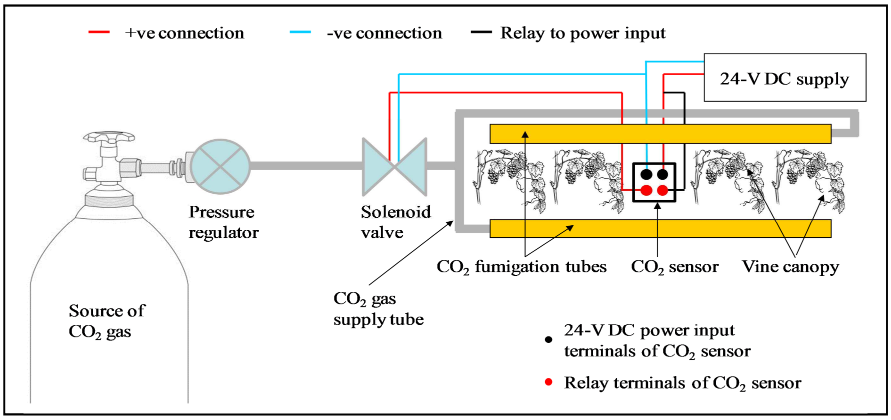

Figure 1: The major components of the prototype CO2InOTC system.

Assessment of [CO_2] spatial distribution

A multi-port IRGA was used to measure the spatial distribution of [CO_2] within the OTC. The details of design, operation and port selection are published elsewhere (Mollah et al. 2011).

CO2InOTC trial I – winter 2011

In May 2011, after leaf fall, but before the vines were pruned, the CO_2InOTC system was assembled inside a single OTC (Fig. 2). The objective of this trial was to determine the feasibility of the CO_2InOTC system and if so, estimate the usage of CO_2 gas to calculate the overall cost of the CO_2InOTC system. Data were collected for about 10 hours (the duration of sunlight) during each day on 3 and 4 May 2011.

Thirty two sampling locations were pre-determined representing the entire volume of space contained by the chamber; these were arranged in horizontal and vertical planes. Samples were collected at 0.75-m, 1.3-m and 1.7-m above the soil surface. The coordinates (x, y, z) of each location were recorded relative to the centre of the OTC (x, y, z = 0, 0, 0).

The multi-port IRGA was placed inside the OTC (see Fig. 2) and set to automatically log [CO_2] at each of the 32 sampling points, with a 5.33 min interval between each full set of measurements. Date, time, wind speed, and wind direction were logged with every individual [CO_2] measurements. The height of the CO_2 controller sensor and the height and spacing of fumigation tubes were adjusted until the data indicated that the desired spatial distribution of [CO_2] inside the OTC was achieved.

CO_2InOTC trial II – summer 2011/12

The CO_2InOTC system and multi-port IRGA were set up as in Trial I, in the same vineyard, but utilising a different panel of vines, and run between December 13th and 16th 2011 with fully grown vines (Fig. 3). As with Trial I, 32 sampling points in both horizontal and vertical planes inside the OTC were pre-determined and their coordinates (x, y, z) recorded. Samples were collected at 0.75-m, 1.35-m and 1.75-m above the soil surface, with an additional sampling point located 2.56-m above the soil surface, at the tip of the highest shoot. Nine different fumigation scenarios were trialled, comprising of two CO_2 fumigation tube heights; two angles of fumigation jets, two heights of CO_2 controller sensor and with the circulating fan component of the heating system on or off (Table 1).

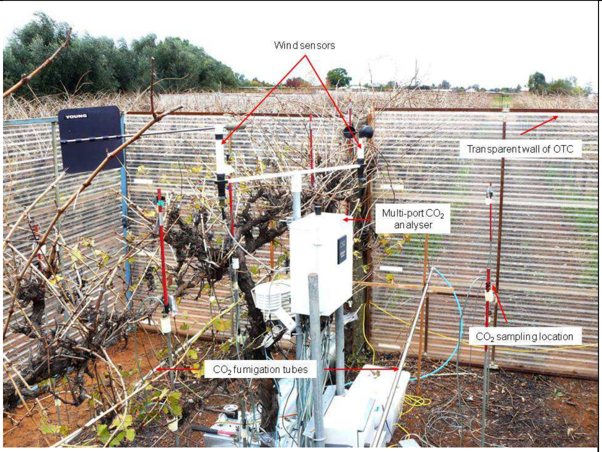

Figure 2: Set up for CO_2 injection, control and monitoring inside an OTC for Trial I (winter)

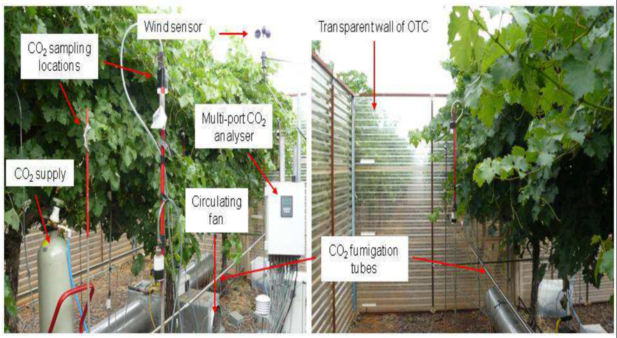

Figure 3. Set up for CO_2 injection, control and monitoring inside an OTC for Trial II (summer).

Statistical methods and contour mapping

There were 3,408 data points for the winter trial and 10,371 data points for the summer trial available for analysis. The data consisted of [CO_2], wind speed and wind direction readings collected by the multi-port IRGA. All data collected were summarised using means, medians and standard deviations. The data collected for the summer trial were categorised according to the scenarios (Table 1). One sample sign tests and Student's t-tests were performed to identify the scenario with the best spatial distribution. The Kriging method of spatial interpolation (point type), employing a linear variogram model, was used to draw the contour maps of [CO_2] for the selected scenarios using Surfer 7 software (Golden Software Inc, CO, USA).

Table 1:.Set-up scenarios tested during Trial II, summer 2011. The fumigation tubes were set to a spacing of 1.3 m and the jets were facing inwards, towards the trellis, in all cases.

Scenario	Fumigation tube height (m)	Jet orientation	CO_2 sensor height (m)	Circulating fan
1a	**1.3**	**Parallel to ground.**	**1.95**	**Off**
1b	**1.3**	**Parallel to ground.**	**1.95**	**On**
2a	**1.3**	**Parallel to ground.**	**2.3**	**Off**
2b	**1.3**	**Parallel to ground.**	**2.3**	**On**
3a	**1.3**	**45° downwards.**	**2.3**	**Off**
3b	**1.3**	**45° downwards.**	**2.3**	**On**
4a	**0.75**	**Parallel to ground.**	**2.3**	**Off**
4b	**0.75**	**Parallel to ground.**	**2.3**	**On**
5	**0.75**	**45° downwards.**	**2.3**	**Off**

3 Results

Optimal positioning of system components

Manually relocating the fumigation tubes in Trial I, whilst monitoring the [CO_2] at each sampling location, resulted in the most uniform spatial distribution around the vines being achieved by setting the fumigation tubes at a distance of 1.4-m apart from each other, with the trellis in the centre, and 1.5 m above the soil surface (data not shown). The CO_2 sensor was placed at the centre of the OTC at a height of 1.75-m, just above the top cordon wire.

In Trial II, a total of nine 'scenarios' (four with and without the circulation fan running, one only without the fan, see Table 1) were tested with a full canopy on the vines, using various combinations of fumigation tube height, jet angle, CO_2 sensor position and with the circulating fan on or off. Analysing the results with a 'one sample sign test' showed that the mean [CO_2] at different heights inside the grapevine canopy were significantly different from the target 550 µmol mol^{-1} for scenarios 1a, 1b, 2b, 4a and 5, hence scenarios 1 & 5 were rejected. Scenario 4b exhibited a relatively high variance (data not shown), so scenario 4 was also rejected. The standard deviation (SD) of [CO_2] for each of the remaining scenarios (2 and 3) was relatively small and consistent, but comparing the mean [CO_2] across all heights, it was scenario 3 that had the most consistent result, combined with the lowest SD (Table 2). Therefore, scenario 3 was selected as the best set up for CO_2 injection inside OTCs.

Table 2: Mean [CO_2] and SD around the grapevine canopy at three heights for the two scenarios where mean [CO_2] did not differ significantly from set point.

	Sampling height above the ground					
	0.75-m		**1.35-m**		**1.75-m**	
Scenario	**Mean [CO_2] (µmol/mol)**	**SD [CO_2] (µmol/mol)**	**Mean [CO_2] (µmol/mol)**	**SD [CO_2] (µmol/mol)**	**Mean [CO_2] (µmol/mol)**	**SD [CO_2] (µmol/mol)**
2a	508	58	603	89	621	113
2b	573	96	594	43	587	123
3a	547	67	603	104	591	83
3b	511	58	582	73	593	73

Spatial distribution of [CO_2]

The CO_2InOTC system encloses three vines along a vine row (one panel), but the central vine is used for physiological measurements and sample collection wherever possible to minimise edge effects. Consequently, whilst maintaining as even a spatial distribution of [CO_2] as possible is desirable, it is particularly important that the central vine has the minimum possible temporal variation in elevation of [CO_2] above background levels, which averaged approximately 375 µmol mol^{-1} during the day, increasing by about 20 µmol mol^{-1} during the night to 395 µmol mol^{-1}.

As this was an open top system, temporal variation in [CO_2] was likely to be driven by variation in wind speed and direction. The former ranged between 0 and 3.4 m s^{-1} during the second test period, but averaged only 0.7 m s^{-1}. In fact, the middle vine received the desired amount of CO_2 regardless of wind direction, because injection occurred all around that vine and the CO_2 addition was controlled based on the [CO_2] above it. So, the system was largely independent of wind direction.

The system could also be fitted with a sensor to shut off the CO_2 supply if wind speed exceeds the set target, thus minimising the loss of CO_2 at wind speeds that prevent effective control. However, this was not implemented in our trials as such speeds were not encountered during our testing.

During Trial 1, where there were no leaves on the vines to influence air movement and the CO_2 sensor was positioned at 1.75 m, the influence of wind on the spatial distribution was evident with the highest [CO_2] measured inside the OTC on the windward side (results not shown). During Trial 2, where the jet angle and CO_2 sensor height were optimised and a full canopy was present, the best spatial distribution of [CO_2] was observed with scenario 3 (see above) and exhibited a 2*SD (95% confidence level) of approximately 25% of set-point horizontal (Fig. 4) and vertical (Fig. 5) planes, with or without the circulating fan in use. This was comparable to the spatial distribution of [CO_2] achieved in wheat fields during the AGFACE experiments (Mollah et al*.* 2010, Mollah et al*.* 2011) and as good as or better than that reported for an area distributed FACE (Bunce 2011), a system with which the CO_2InOTC system is somewhat similar.

The results presented here for the CO_2InOTC system are most likely to be influenced by the artefacts of the OTC, such as restricted airflow, altered temperature and RH, reduced interception of radiation and precipitation on and around the crop inside the OTC. Although the system was designed to work within the OTC, due to the need to control air temperature and minimise CO_2 use, a similar system could be established in a free-air situation. If successful, it would provide both a cost-effective and portable solution, not only for grapevines but potentially for other perennial orchard crops like apples, pears, etc. with shallow canopies.

FACE systems that inject pure CO_2 in the atmosphere generate a large and highly variable [CO_2] around the fumigation tubes (Okada et al*.*2001; Mollah et al*.*2009; Mollah et al*.*2011). However, the CO_2InOTC system uses very low injection pressure i.e. 40 kPa compared with 500 kPa for AGFACE. Consequently, it was expected that there would be a smaller and less variable [CO_2] near the fumigation tubes for our system. This was demonstrated by the results, e.g., a mean of 582 µmol mol^{-1} inside the grape canopy at 65 cm (tube spacing 1.3 m) from the fumigation tube with a SD of 73 µmol mol^{-1} (Fig. 5b) compared with a mean of about 800 µmol mol^{-1} and a SD of 450 µmol mol^{-1} for a similar distance in AGFACE (Mollah et al*.*2011). The CO_2InOTC system injects CO_2 downward (not targeting canopy) at a 45º angle which will also minimise the biological impacts, if any, of pulses of high CO_2.

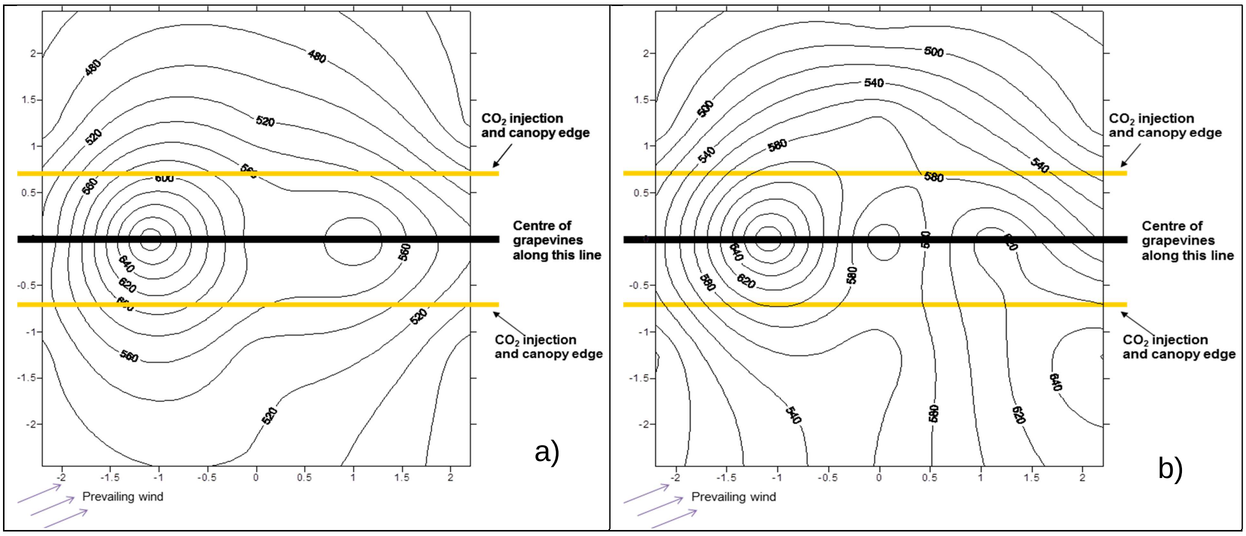

Figure 4. Top view of spatial distribution of [CO_2] at a) 1.35 m and b) 1.75 m above the soil surface inside the OTC during Trial II (Summer), scenario 3b (heating system on).

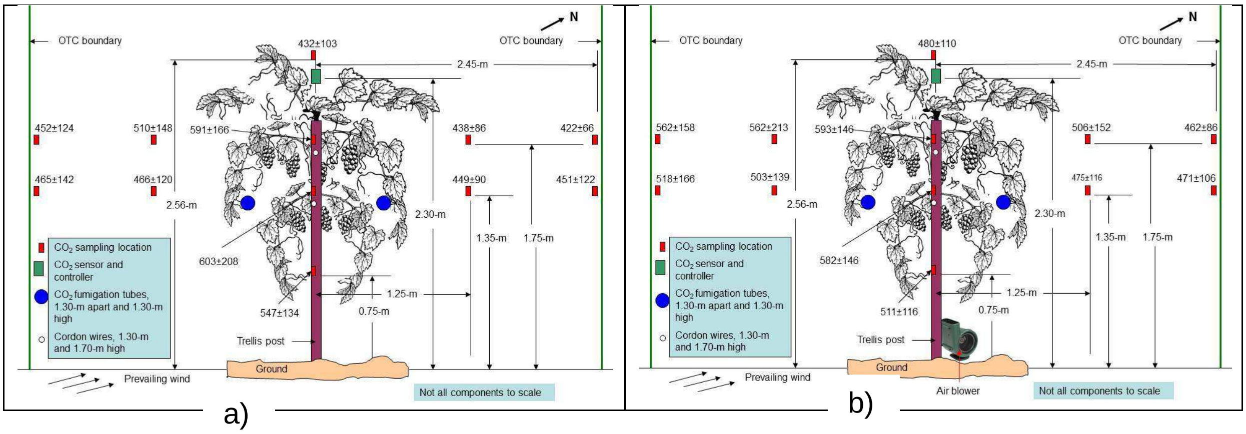

*Figure 5. The mean [CO_2] ± 2*SD (for 95% confidence level) in and around grapevine with full canopy inside an OTC for a) scenario 3a (circulating fan off) and b) scenario 3b (circulating fan on).*

Cost-effectiveness of the CO_2InOTC system

The data from the AGFACE experiment showed that for an average relative humidity (RH) of 44%, average temperature of 17ºC and median wind speed of 0.7 m s^{-1} the CO_2 consumption was 318 g m^{-3} h^{-1} (unpublished). On the other hand, the CO_2 consumption inside the OTC in the vineyard was 60 g m^{-3} h^{-1}, less than one-fifth of AGFACE, for similar conditions, e.g. average RH of 35%, average temperature of 20.7ºC and median wind speed of 0.7 m s^{-1}. In the early 1990s, OTCs were built in UK to expose plants in the field to elevated concentrations of CO_2 (Ashenden et al*.* 1992). The CO_2 consumption in those OTCs was estimated to be 316 g m^{-3} h^{-1}, also much higher than the consumption reported here and similar to AGFACE.

At the wind speeds occurring during testing, the CO_2InOTC system on average used 4 kg of CO_2 per hour. This low consumption of CO_2 can be attributed to the low pressure used for injection of CO_2 (40 kPa vs 500 kPa for AGFACE) and the mode of injection. Inside the OTC, CO_2 was released underneath the canopy from both sides of the vine row and pointing towards the ground at 45º angle, so the jets of CO_2 from both sides could converge underneath the canopy. The mixture of CO_2 and air travelled up through the canopy and reached the CO_2 sensor and controller near the top of the canopy (2.3-m above the ground, Fig. 6). This mode of injection minimised the loss. In FACE rings, CO_2 is released above the canopy from the upwind side, so the prevailing winds can transport the mixture of CO_2 and air to the downwind side of the ring. This requires high pressure release and large amount of CO_2 is lost through turbulence.

There have been very few experiments studying the impact of e[CO_2] on grapevines. Recently, a FACE system was established at Geisenheim, Germany to test the effects of e[CO_2] on grapevines, but this has not yet been switched on. In the late 1990s, a FACE system for grapevines was established in Italy (Bindi et al. 2001b), similar to the concept of ForestFACE (Hendrey et al. 1999). There are no published data on CO_2 consumption for either system and for the former at least, data are not available (pers. com. Bindi 2013). However, the ForestFACE study reported that CO_2 consumption was much higher than an OTC on an absolute basis but similar to that of the OTC on a per unit volume basis. The consumption averaged 50 g m^{-3} h^{-1} for average wind speed of 1.5 m s^{-1} (Hendrey et al. 1999) and this may be indicative of the Italian system, since it used a similar design.

4 Conclusions

The CO_2InOTC system is a cost-effective way to inject CO_2 inside an OTC to elevate [CO_2] in and around grapevines or other woody perennial row crop. The spatial distribution of CO_2 gas by CO_2InOTC with or without blower assisted air circulation was as good as or better than the distribution reported for several other FACE systems.

5 Acknowledgements

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6 References

Ashenden, T. W., Baxter, R., Rafarel, C. R. (1992). An inexpensive system for exposing plants in the field to elevated concentrations of CO_2. *Plant, Cell and Environment 15*, 365 – 372.

Barton, C. V M., Ellsworth, D. S., Medlyn, B. E., Duursma, R. A., Tissue, D.T., Adams, M. A., Eamus, D., Conroy, J. P., McMurtrie, R. E., Parsby, J., Linder, S. (2010) Whole-tree chambers for elevated atmospheric CO2 experimentation and tree scale flux measurements in south-eastern Australia: The Hawkesbury Forest Experiment. *Agricultural and Forest Meteorology 150*, 941-951.

Bindi, M., Fibbi, L., Miglietta, F. (2001a) Free air CO_2 enrichment (FACE) of grapevine (*Vitis vinifera* L.): II. Growth and quality of grape and wine in response to elevated CO_2 concentrations. *European Journal of Agronomy 14*, 145-155.

Bindi, M., Fibbi, L., Lanini, M., Miglietta, F. (2001b) Free air CO_2 enrichment (FACE) of grapevine (Vitis vinifera L.): I. Development and testing of the system for CO_2 enrichment. European *Journal of Agronomy 14*, 135-143.

Bunce, J., A. (2011) Performance characteristics of an area distributed free air carbon dioxide enrichment (FACE) system. *Agriculture and Forest Meteorology 151*, 1152 – 1157.

Carter, T. R., Jones, R. N., Lu, X., Bhadwal, S., Conde, C., Mearns, L. O., O'Neill, B. C., Rounsevell, M. D. A., Zurek, M. B. (2007) New assessment methods and the characterisation of future conditions. In 'Climate Change 2007: Impacts, adaptation and vulnerability'. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (Eds ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson) pp. 133 -171. (Cambridge University Press: Cambridge, UK).

Edwards, E. J., Unwin, D., Mazza, M., Downey, M. O. (2012). Hot and getting hotter - how will a warming climate affect warm climate viticulture? *Wine & Viticulture Journal, 27(4)*, 44–48.

Gonçalves, B.; Falco, F.; Moutinho-Pereira, H.; Bacelar, E.; Peixoto, F., Correia, C. (2009) Effects of elevated CO_2 on grapevine (*Vitis vinifera* L.): volatile composition, phenolic content, and in vitro antioxidant activity of red wine. *Journal of Agricultural and Food Chemistry 57*, 265-273.

Hendrey, G. R., Ellsworth, D. S., Lewin, K. F., Nagy, J. (1999) A free-air enrichment system for exposing tall forest vegetation to elevated atmospheric CO_2. *Global Change Biology 5*, 293-309.

Jones, G. V. (2005) Changes in European winegrape phenology and relationships with climate. *Proceedings of the XIV International GESCO Viticulture Congress, 23-27 August 2005, Geisenheim,* Germany. pp54-61.

Langley, J. A., Mozdzer, T. J., Shepard, K. A., Hagerty, S. B., Megonigal, J. P. (2013) Tidal marsh plant responses to elevated CO_2, nitrogen fertilization, and sea level rise. *Global Change Biology 19*, 1495-1503.

Mollah, M. R., Norton, R. M., Huzzey, J. (2009) Australian grains free air carbon dioxide enrichment (AGFACE) facility: design and performance. *Crop & Pasture Science 60*, 697 – 707.

Mollah, M. R., Fitzgerald, G. (2010) The size of free air carbon dioxide enrichment (FACE) rings affects overall system performance: An Australian experience. Proceedings of 15th ASA Conference, 15 – 19 November 2010, Lincoln, New Zealand.

Mollah, M. R., Partington, D., Fitzgerald, G. (2011) Understand distribution of carbon dioxide to interpret crop growth data: Australian grains free-air carbon dioxide enrichment experiment. *Crop & Pasture Science 62*, 883 – 891.

Moutinho-Pereira, J., Gonçalves, B., Bacelar, E., Cunha, J. B., Coutinho, J., Correia, C. M. (2009) Effects of elevated CO_2 on grapevine (*Vitis vinifera* L.): Physiological and yield attributes. *Vitis 48*, 159–165.

Moutinho-Pereira, J. M., Bacelar, E. A., Goncalves, B., Ferreira, H. F., Coutinho, J. F., Correia, C. M. (2010) Effects of open-top chambers on physiological and yield attributes of field grown grapevines. *Acta Physiologiae Plantarum 32*, 395–403.

Okada, M., Lieffering, M., Nakamura, H., Yoshimoto, M., Kim, H. Y., Kobayashi, K. (2001) Free-air enrichment (FACE) using pure CO_2 injection: system description. *New Phytologist 150*, 251–260.

Rusticucci, M., Somerville, R., Stocker, T. F., Whetton, P., Wood, R. A., Wratt, D. (2007) Technical Summary. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Scripps Institution of Oceanography (2012) Atmospheric CO_2 for July 2012. Mauna Loa Observatory, Hawaii. http:CO_2Now.org (Accessed 6 September 2012).

Webb, L. B., Whetton, P. H., Barlow, E. W. R. (2011). Observed trends in winegrape maturity in Australia. *Global Change Biology 17*, 2707 – 2719.