Wetlands (2015) 35:193–205
DOI 10.1007/s13157-014-0614-2

ORIGINAL RESEARCH

A Free Air CO_2 Enrichment (FACE) Facility in a Wetland to Study the Effects of Elevated Atmospheric Carbon Dioxide: System Description and Performance

S. Sánchez-Carrillo · R. Morea · L. Serrano-Grijalva · A. Meco · R. Sánchez-Andrés

Received: 24 March 2014 / Accepted: 17 December 2014 / Published online: 4 January 2015

Abstract The Free Air CO_2 Enrichment (FACE) system has proved suitable for exposing plants to elevated [CO_2] with minimal disturbance of their natural environment. Here we describe a FACE facility in a floodplain wetland in detail and, additionally, its performance after the first year of operation (2012). The FACE system consisted of six 3-m diameter emission rings in which *Phragmitesaustralis* was grown. The target [CO_2] was 550 μmol mol^{-1} and fertilization was carried out continuously. Daily temporal [CO_2] performance was adequate with 61 and 83 % of air samples at the ring's centre having a [CO_2] within 10 and 20 % of the target, respectively, with values closest to their target during summer months and daytime. Spatial [CO_2] distribution showed no significant gradients across the ring. Increased wind speed improved the system's spatial performance, as [CO_2] was within ±10 % of the target in the whole ring. Across the entire fertilization season, CO_2 requirements for maintaining a mean [CO_2] of 582 μmol mol^{-1} in wetland plots averaged 17.4 kg CO_2 $ring^{-1}$ day^{-1}. Our requirements (2.5 kg CO_2 m^{-2} day^{-1}) were very low compared to other FACE systems, demonstrating its high potential to study the effects of elevated CO_2 in wetlands at low cost.

Keywords Elevated carbon dioxide · Free-air CO_2 enrichment (FACE) · Performance control · Design · Wetland

Introduction

The increase of atmospheric [CO_2] from pre-industrial times is amongst the most significant impacts of human activity on global climate (IPCC 2007; Solomon et al. 2007). One of the main challenges facing research into elevated [CO_2] effects on ecosystems and vegetation is the simulation of high [CO_2] levels without changing the physical environment of growing vegetation. Free Air CO_2 Enrichment (FACE) systems have proven suitable to expose plants to elevated [CO_2] with minimal disturbance of their natural environment (solar radiation, temperature, humidity and wind) which can influence their response to elevated [CO_2] (McLeod and Long 1999). FACE has been successfully used since the late 1980s to expose agricultural crops, grasslands, forest plantations and desert shrubs to elevated [CO_2] (Hendrey 1994; Kimball et al. 1995; Jongen et al. 1995; Miglietta et al. 1997; see Okada et al. 2001 for a further explanation of FACE advantages). However, although FACE can be considered superior to other CO_2 exposure techniques, most studies in wetlands have been performed using the open-top chamber technique (e.g., Ziska et al. 1990; Arp et al. 1993; Rasse et al. 2005). Although differences between both open-top chambers and FACE are not conclusive, in some cases the environment inside the chamber can induce greater plant growth and the FACE approach is preferred for many studies because both absolute and relative responses to elevated C02 can be reliably obtained (Kimball et al. 1997; De Graaff et al. 2006). In fact, FACE

S. Sánchez-Carrillo (✉) · L. Serrano-Grijalva
Department of Biogeochemistry and Microbial Ecology, National Museum of Natural Sciences MNCN-CSIC, Serrano 115 dpdo, 28006 Madrid, Spain
e-mail: sanchez.carrillo@mncn.csic.es

R. Morea
Institute of Optics "Daza de Valdés" IO-CSIC, Serrano 121, 28006 Madrid, Spain

A. Meco · R. Sánchez-Andrés
Royal Botanic Garden RJB-CSIC, Pza de Murillo 2, 28014 Madrid, Spain

technology was developed in order to expose whole-ecosystems to elevated CO_2 (Calfapietra et al. 2010) and to avoid chamber effects on microclimate (Hendrey and Kimball 1994; Miglietta et al. 2001a). FACE has only been implemented to account for wetlands such as boreal peatlands (bogs; Hoosbeek et al. 2001; Miglietta et al. 2001b) and rice ecosystems (Okada et al. 2001; Guo et al. 2012), but not to date in marshes which require some technological adjustments to account for emergent vegetation and higher water levels.

FACE technology has developed considerably since the first experiments carried out in 1970s (Harper et al. 1973; Lewin et al. 1992). Typically, FACE systems consist of a circular structure (commonly referred to as a ring) constructed from pipes (vertical or horizontal) that surround the vegetation. These pipes emit CO_2 in order to obtain a zone with higher [CO_2] than the surrounding ambient atmosphere. Generally speaking, tall vegetation requires large rings with multilevel (vertical) emission pipes; whereas small rings with emission pipes located at a single height may be adequate for short vegetation, although it depends on the environment and conditions where the experiment is performed. The main limitations of traditional FACE systems are the major capital expenditure they entail, the complex CO_2 emission structures, the amount of gas required to obtain a prolonged exposure to elevated CO_2, and the local environment constraints. Moreover, the use of blowers or fans to predilute and evenly mix the injected CO_2 with ambient air has high power requirements and requires significant infrastructure. Notwithstanding, the use of fans during periods with low wind speeds has been shown to conserve enough CO_2 to recover the infrastructure costs in a FACE experiment performed in a forest (Lewin et al. 2009). Under some conditions, fans can perturb the micro-meteorological conditions inside the ring thus affecting atmospheric stability (He et al. 1996; Okada et al. 2001). The release of pure CO_2 instead of an air-CO_2 mixture has been shown to be a reliable alternative to conventional systems, having been used successfully in different locations (Okada et al. 2001; Miglietta et al. 2001a, b). Pure CO_2 is emitted at high pressure and velocity, through a large number of tiny holes (gas jets). Therefore a quick and efficient mixing of CO_2 inside the ring is obtained, according to the theory of fluid mechanics (Miglietta et al. 2001a). FACE facilities installed in marshlands, peatbogs or rice paddy fields (also in other irrigated crops) must be designed for environmental conditions that include the periodic inundation of soils. The ring structures and emission pipes must be able to withstand periodic inundation and the equipment must be adapted to operate under high humidity conditions.

We know of no previous study using FACE facilities to investigate the effects of high [CO_2] in wetlands. Although one study evaluated the effects of elevated [CO_2] under greenhouse conditions on the common reed *Phragmites australis* (Mozdzer and Megonigal 2012), there are no studies assessing the response of *P. australis* to elevated [CO_2] under field conditions. It is important to assess the effects of predicted increases in atmospheric [CO_2] on wetland ecosystem function and structure. This will allow us to predict the extent to which these changes could affect their capacity to provide numerous environmental services, including global change mitigation. The SAWFACE (Semi-Arid Wetland FACE) project is the first experiment to grow reed under elevated [CO_2] without using enclosures. It started in 2009, with design trials carried out in 2010–11. The FACE facility was set up in 2012 with a second year of enrichment being carried out in 2013. Here we describe in detail the design and construction of the FACE facility and the system's performance during the 2012 growing season (May–September).

Material and Methods

Site Description

Las Tablas de Daimiel National Park (TDNP) is a semiarid floodplain wetland located in central Spain (39°08′N, 3°43′W). The maximum inundated area is 16 km^2 with an average water depth of 0.90 m. TDNP is situated at the outlet of a 13,000 km^2 catchment that overlays a 5000 km^2 aquifer. The wetland's hydrology is currently fluctuating, with long drought periods associated with groundwater overexploitation by irrigation practices (Sánchez-Carrillo and Álvarez-Cobelas 2010). From 2004 to 2009 the wetland experienced one of the greatest droughts of the last 50 years, and peat fire threatened to destroy the entire wetland. Subsequently (2010–2014) the ecosystem experienced highest mean annual water level in the last 30 years. The Gigüela River is the only water input to TDNP, although from 2012 groundwater levels are rising and some springs are also feeding the wetland.

The soils of TDNP are slightly saline SO_4-rich histosols, and many areas have high organic matter content. The soil is mainly dominated by sand and silt (40–60 % each), with clay comprising only a minor proportion (5–20 %; Rodríguez-Murillo et al. 2011). The species *Phragmites australis* (Cav.) Trin. ex Steudel (common reed) and *Cladium mariscus* (L.) Pohl (cut sedge) dominate (>90 % cover) the wetland in high flood periods. However, cut sedge, the least productive emergent species in the TDNP (Alvarez-Cobelas and Cirujano 2007), is in serious decline. When inundation is low for long periods of time most of the wetland area is colonized by terrestrial plants (scurvy grass and horseweed), which cover most of the non-vegetated dry wetland zones in spring and summer respectively. The maximum height of reeds growing in inundated soils was 1.56 m on average whereas in dry zones the maximum height was 2.04 m (Ortiz-Llorente 2013). Further information about this wetland can be found in Sánchez-Carrillo and Angeler (2010).

FACE Facility Description

The FACE facility was installed within the wetland (Fig. 1), in an area (≈900 m^2) which has been covered by common reed during at least the last 25 years. The experimental area consisted of 6 octagonal CO_2 enrichment rings (FACE plots) together with 6 control plots maintained at present day [CO_2] (Fig. 1). FACE and control rings were distributed randomly in the experimental area maintaining a distance greater than 6 m between plots. Experimental plots were regularly arranged for logistical reasons (fencing, access gateways, wiring, pipes, etc.). The abundance of wild boars in the wetland forced us to minimize the size of the experimental area and install fencing to protect equipment and ring structures. Each FACE ring was 3 m in diameter (≈7 m^2/plot) and consisted of eight 1.2-m long polyethylene pipes (emission pipes) with a diameter of 16 mm (thickness of 0.5 mm) arranged to make an octagon (Fig. 2a). Each emission pipe was suspended horizontally at 20–30 cm above the macrophyte canopy, using eight stainless steel poles (4-m of height) located at the vertices of every octagon. These were assembled at the top with a detachable steel structure also forming an octagon. The lower part of the poles was welded to flat stainless steel plates, which were attached to the wetland soil using perforated concrete blocks. This increased the octagon structure's stability during flooding. The height of the emission tubes was regulated weekly according to vegetation height during its growth cycle by using stainless steel chains which were attached to the upper octagon structure (Fig. 2a).

The gas used for enrichment was liquefied ultrapure CO_2 stored in a VT21 tank (≈40,000 kg), located outside the wetland (~400 m distance). Liquid CO_2 was supplied to electrical heat exchangers which vaporized it. The resulting CO_2 gas was channelled to a pressure regulator that reduced line pressure to 500–1,000 kPa. Finally CO_2 gas was piped to FACE plots through 16-mm diameter polyamide tubing which was buried to minimize the risk of damage.

FACE rings were based on directionally controlled release of pure CO_2 from jets (micro-holes) located in the emission pipes. By releasing CO_2 through the jets the gas reaches sonic velocity so that, consistent with the theory of fluid mechanics, it creates a shock wave at the outlet and substantially improves mixing with air (Miglietta et al. 2001a). The reason for using micro-holes is to obtain a rapid mixing between CO_2 and air, which achieves a significant simplification of construction and reduced capital cost of the FACE facility. The study of

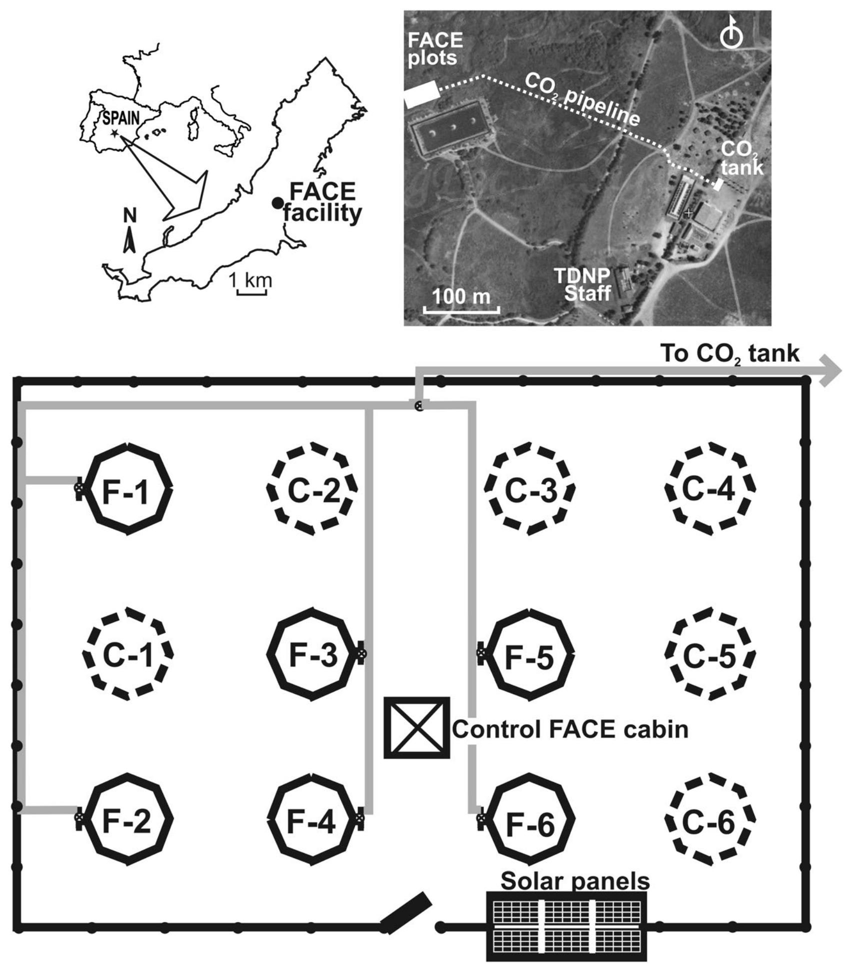


Fig. 1 Location of the wetland FACE facility and plan views showing the CO_2 cryogenic tank arrangement in the wetland area and the system layout showing the fertilized (F) and ambient (C) rings, as well as the gas supply lines (*grey lines*)

Fig. 2 Wetland FACE facility details. **a** CO_2 fertilized rings showing the octagon arrangement of emission tubes, the pressure regulator and solenoid valves, and the plot partition among vegetated and unvegetated zones. **b** the casing control cabin showing the main equipment and circuits used to run the FACE facility

Miglietta et al. (2001a) stated that such dilution is almost independent of the absolute CO_2 flow rate, as when the pressure is increased in the pipe, the higher density of the released gas enhances the shock-wave effect and mixing is further enhanced. Theoretically, considering a standard atmospheric pressure of 101.3 kPa, sonic velocity is achieved when the pressure inside the pipe is greater than 50 kPa (Miglietta et al. 2001a), which occurred 86 % of the time during our fertilization period. In order to produce the micro-holes each emission pipe was perforated with an ultra-short laser pulse (propellant; diameter <300 μm; Laser Service of the University of Salamanca) every 2.4 cm, which gave a total of 50 jets per emission pipe and 400 jets per FACE ring. As fans were not used, it was unnecessary to build any additional control plots in order to evaluate ring structure effects. An automatic pressure regulator (1/4" electronic proportional pressure regulator MPT40-P3HPA12AS2VD1A, Parker) controlled the amount of CO_2 released in each FACE ring, and was operated by supplying variable voltage (0–10 V DC) that was translated into a pressure value (0–150 kPa). A digital-to-analog converter (DAC USB 3103, Measurement Computing Inc.) was used to convert the digital signal into an analog voltage value that operated the pressure regulators in each FACE plot. The maximum CO_2 gas pressure at the emission pipes was limited to 140 kPa as a result of the resistance of supply tubes. For budgetary reasons two IRGAs (Infra-red gas analyzer; WMA-

4 PP-Systems), located in FACE-1 and FACE-5 plots, were used to measure the atmospheric [CO_2] in the ring centre at canopy height in fertilized plots. Another additional IRGA was installed in the control plot C-3. This measured the temporal trend of ambient [CO_2] in the control plots, and any CO_2 contamination events. The operational principle of the directional control of CO_2 emission was based on releasing the gas from horizontal pipes located in the upwind side of the FACE octagon plot following Okada et al. (2001): when the wind speed was over 0.5 m s−1, CO_2 was released from the most upwind emission adjacent pipes (2–4 pipes); when there was no wind (wind speed <m s^{-1}), CO_2 was emitted from every pipe (8 pipes in total). The use of two sets of pipes with holes located at different emitter spacing has not been considered in this design in order to simplify the ring structure and operation considering the small size of the FACE plots used. CO_2 was managed using solenoid on/off valves (VE 151 HV, Parker), which commutated depending on the wind direction and velocity recorded by two 2D ultrasonic anemometers (WINDSONIC, Gill Instruments) located at the top of FACE-3 and FACE-5 plots (see below for details). Solenoid valves were connected independently to the respective emission pipes of the FACE ring by means of 10-mm diameter, polyamide tube. These electrically activated valves were operated by relay controllers (1ADPDT R232 24-channel Relay Controller, National Control Devices Inc.). Wind data, as well as other additional meteorological measurements (2 IR-120 infra-red remote temperature sensors for leaf and soil temperatures and a NR-Lite net radiometer, both from Campbell Sci.) were stored in a data logger module (CR1000, Campbell Sci.).

FACE Facility Control and Operation

The operation of the FACE system was carried out from a casing control cabin (Fig. 2b). All equipment and various circuits operating at 12 V and 24 V DC were installed and connected to a laptop computer, which ran the facility. Power supply to the FACE facility was provided by solar panels (700 W) and rechargeable gel batteries, to avoid any damage by lightning. Measurements obtained by the IRGA located at plot FACE-1 were used for the operation of F-1, F-2, F-3 and F-4plots, whereas those recorded by the IRGA in FACE-5 were computed for the [CO_2] control of F-5 and F-6 plots. Since data from wind sensors located at FACE-3 and FACE-5 plots were very similar (see results section), the use of records to compute CO_2 emissions of remaining plots was established randomly (FACE-3: F-1, F-2, F-3 and F-4; FACE 5: F-5 and F-6).

All variables were processed by means of a proportional integral differential (PID) algorithm programmed in Visual Basic (Microsoft®). The PID algorithm was a modified version of that described by Lewin et al. (1994) with discrete time signals. The PID-type algorithm calculates the voltage provided to the pressure regulator, which controls the pressure of CO_2 released into the FACE rings, according to the [CO_2] reached in the previous time interval and a target [CO_2] value. The PID algorithm regulated the CO_2 flow into the rings until the proposed target level was reached. The selected target [CO_2] was 550 μmol mol^{-1}. Briefly, the output signal to the CO_2 flow controller (F_{tot}) depends on the integral (F_{int}), proportional (F_{prop}) and differential (F_{diff}) CO_2 flows and wind (F_{wind}) components of the algorithm. Variables F_{int}, F_{prop} and F_{diff} are components of a standard PID algorithm using negative feedback whereas F_{wind} anticipates changes in gas demand as a result of changes in wind speed and direction. The algorithm used average [CO_2] every 56 s (1.6 s was the measuring interval of IRGAs) and the average wind speed every 60 s (wind velocity was measured every second with the ultrasonic anemometers). The integration time was variable, oscillating from 56 to 185 s. The algorithm was also designed to compute the directional control of the CO_2 emission when the wind speed was over 0.5 m s−1 (for wind speed <0.5 m s^{-1} CO_2 was emitted by all emission tubes).

Experimental Procedures

Some areas within the FACE facility area were manually harvested in November 2009 using brush cutters in order to install the delivery poles and the ring structures. The installation of ring structures, pipes and equipment was extended throughout 2010, and the first calibration and operation test was carried out during early 2011. Due to extensive flooding of the wetland from December 2009 to July 2011, reeds did not sprout spontaneously in the study area during either the 2010 or 2011 growing seasons. Reeds were planted in May 2012 from rhizomes collected in the wetland close to the FACE facility area. The first fertilization period was performed during the 2012 growing season from May to October, maintaining CO_2 emissions during day and night time. The FACE facility was under operation 86 % of the entire experimental period with pauses of less than 3 full days, due to equipment maintenance or malfunction. Because the aim of this experiment was to test the effects of CO_2 enrichment on wetland as a system, half of both FACE and Control plots were kept unvegetated during the fertilization by means of clipping new shots of reed weekly. Clearly, no soil process is directly affected by elevated CO_2 alone; however, some soil processes can be affected indirectly by means of vegetation responses to elevated CO_2 in the root zone. Therefore in order to distinguish these effects, half the plots were kept free of vegetation.

Temporal performance was assessed using 1 min average [CO_2] measured at the centre of FACE and control rings. Since a CO_2 concentration gradient along wind direction is unavoidable within a FACE ring (Miglietta et al. 1996), spatial performance was determined as the difference between the [CO_2] measured at canopy height in the centre of the ring and [CO_2] measured at any other point of the ring at the same height. For this purpose, during 5 non-consecutive days (mid-March 2012), a manually operated multiport gas sampler connected to an IRGA (WMA-4 PP-Systems) was used to take air samples in 12 sampling points, evenly spaced within the FACE plot F-5 at canopy height. Tests were done from 07:00 to 21:00 h with two observations taken during night (22:00–01:00 h). Because at the time of this test no plants grew in FACE rings, a height of 1.5 m was assumed to be representative of the mean reed height in the wetland. As IRGA measurements of [CO_2] are taken during 1.6 s, every 5 s a measurement was taken at each sampling point (1 record per sampling site per minute; 5×12=60). Simultaneously [CO_2] was sampled at the same frequency in the centre of the FACE ring using an additional IRGA. Periodic auto zeros were programmed in both IRGAs, performed every 5 min for providing automatic correction for sample cell contamination, detector sensitivity variations and pre-amplifier gain changes. Throughout the spatial test the both IRGA were cross-calibrated daily.

FACE system performance was computed as an assessment of the temporal and spatial control of [CO_2] within the FACE rings, and also as the overall reliability of the FACE system in supplying CO_2 (Okada et al. 2001) as follows:

$$Target\ achievement\ ratio(TAR) = FACE/set\ point$$

Where *FACE* is the [CO_2] of a sample measured in a FACE ring, *set point* is the [CO_2] target level desired at that time. For a given period or environmental conditions, the fraction of recorded [CO_2] values that were within 10 or 20 % of the target were calculated ($0.9 \leq TAR \leq 1.1$ or $0.8 \leq TAR \leq 1.2$). These fraction limits were calculated using [CO_2] recorded at the ring centre every 1.6 s for 1-min averages, 24-h averages, as well daytime and night time averages. These data were recorded for both the entire observational period (from March to October) and the summer months (from July to September).

To assess CO_2 contamination downwind in adjacent control plots the temporal trends of [CO_2] were compared within control plots, between days with similar wind speed pattern, using those days when the FACE system was not in operation, compared with those in operation (without CO_2 enrichment: 28-Apr, 5-May, 4-Jun, 18-Jun, 4-Jul and 6-Aug). Similarity of daily wind speed time-series was assessed using the Sheaf methodology, a graphical method to compare time-series (Ferrán-Aranaz 2013). Pairs of similar wind speed days, used to assess the CO_2 contamination effects downwind in control plots, were: April 28th vs May 4th and May 5th vs July 8th. The system's ability to control the target [CO_2] was studied through multiple regressions with environmental variables (air temperature, wind speed and direction, net radiation and time). Collinearity was investigated using the variance inflation factor in multiple regressions (Neter et al. 1996). Adjusted R^2 was used for assessing goodness of fit to the models (Zar 1999) while the comparison was assessed computing the Akaike Information Criterion (AIC), based on information theory (Burnham and Anderson 2002). We also used non-linear estimations (i.e., piecewise linear regression) to compute the effects of single environmental variables on [CO_2].

Results and Discussion

Wind and Long-Term System Performance

Daily mean wind speed ranged from 0.3 to 2.8 m s^{-1}, while the mean wind speed for the whole study period was 1.12± 0.87 and 1.18±0.96 m s^{-1} in F-3 and F-5 rings, respectively. Wind speeds in both rings were quite similar for instantaneous records (R^2=0.94, $p<0.01$) as well for daily averages (R^2= 0.90, $p<0.01$). 72 % of the time, wind speed was above 0.5 m s^{-1} (Fig. 3). Wind speeds above 3 m s^{-1} were sporadic (Fig. 3). Maximum instantaneous wind speed was recorded during daytime, achieving 35.6 m s^{-1} (July 5th 21:40). There were significant differences in the daily mean wind speed between daytime and night time (Wilcoxon pairs test $p<0.001$) with the latter experiencing on average less wind (44 % less on average) and having frequent long, still periods. Wind blew more frequently from the south-west (Fig. 3) with no significant differences between day and night time periods (Spearman rank order correlation $r=0.70$ $p<0.05$).

Table 1 shows [CO_2] at the ring center of F-1 and F-5 plots and overall target achievement ratios using 1-min averages and 24-h averages for both the entire observation period and the summer months. For both periods, using 1-min and 24-h records, the average [CO_2] achieved in rings was over the desired target level (550 μmol mol^{-1}), with TAR values slightly lower than 1.1. About 37 and 75 % of the 1-min [CO_2] averages were within 10 and 20 % of the target [CO_2], respectively; using the 24-h averages, 61 and 83 % of the samples were within 10 and 20 % of the target. TAR values as well as limit fractions were best achieved during summer months (Table 1). Larger deviations from target [CO_2] occurred during night time (Table 2). Using only daytime [CO_2], 68 and 90 % of occasions were within 10 and 20 % of the target, increasing the accuracy during summer months (Table 2).

Our performance values at 1-min averages was lower than those reported by other FACE facilities (Nagy et al. 1992: 65–90 %; Miglietta et al. 1997: 74 %; Okada et al. 2001: 48–82 %). The main cause of these differences should be

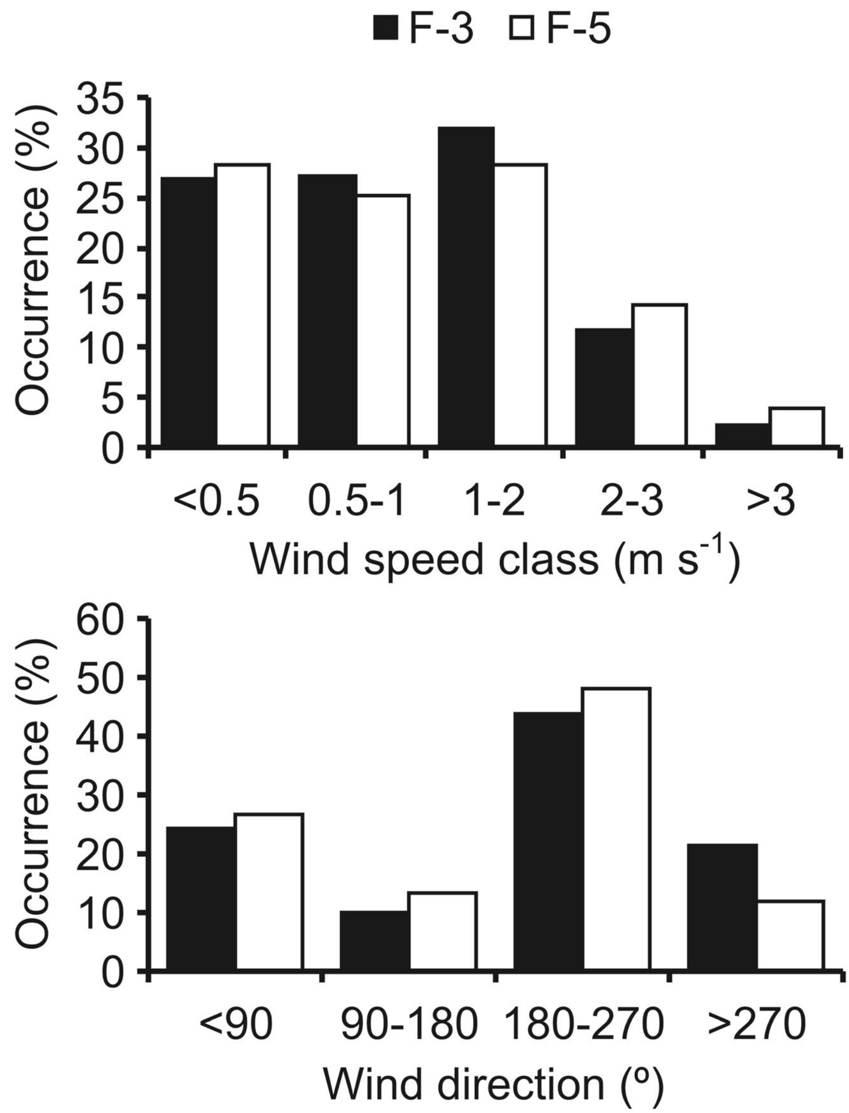


Fig. 3 Wind speed and direction class distribution in ring F-3 and F-5 at the wetland FACE facility during the 2012 experimental season

Table 1 Average [CO_2], overall target achievement ratio (TAR) and fraction of 1-min averages and 24-h averages within ±10 % and 20 % of the target value for two wetland FACE rings during the entire observation period and the summer months

	1-min averages				24-h averages			
			Limit fraction				Limit fraction	
	[CO_2] (μmol mol^{-1})	TAR	±10 %	±20 %	[CO_2] (μmol mol^{-1})	TAR	±10 %	±20 %
Entire period (March–October)								
Ambient	397.3				398.1			
F-1	587.7	1.068	0.37	0.69	587.3	1.068	0.66	0.76
F-5	594.4	1.081	0.39	0.68	593.9	1.080	0.61	0.72
Summer months (July–September)								
Ambient	400.3				399.8			
F-1	584.2	1.062	0.42	0.75	584.6	1.063	0.75	0.83
F-5	581.7	1.058	0.44	0.75	582.1	1.058	0.68	0.82

Table 2 Average [CO_2], overall target achievement ratio (TAR) and fraction of daytime and night time within ±10 % and 20 % of the target value using 1-min averages for two wetland FACE rings during the entire observation period and the summer months

	Daytime				Nighttime			
			Limit fraction				Limit fraction	
	[CO_2] (μmol mol^{-1})	TAR	±10 %	±20 %	[CO_2] (μmol mol^{-1})	TAR	±10 %	±20 %
Entire period (March–October)								
Ambient	396.1				401.3			
F-1	557.9	1.014	0.68	0.85	633.9	1.153	0.34	0.66
F-5	564.0	1.025	0.70	0.85	641.5	1.166	0.36	0.63
Summer months (July–September)								
Ambient	397.2				403.4			
F-1	576.6	1.048	0.73	0.88	664.4	1.208	0.39	0.70
F-5	585.2	1.064	0.75	0.89	677.4	1.232	0.42	0.69

attributed to the wind: whereas wind direction seems to have no effect on [CO_2], from Fig. 4 it is clear that the regulation of [CO_2] to its target value (550 μmol mol^{-1}) was not effective at wind speeds lower than 0.5 m s^{-1}. In fact, when wind velocity was lower than 0.5 m s^{-1}, 1-min average [CO_2] was within 10 and 20 % of the target value only about 27 and 56 % of the time, respectively (Fig. 4). This wind class was recorded between 25 and 30 % of study period time, and is considered the main cause for the difference in our FACE facility [CO_2] control performance with regard to other FACE systems (see Okada et al. 2001). Atmospheric stability, condition which contributes to vertical mixing of air, is affected by wind speed, air temperature, net radiation and roughness surface of the canopy. At the beginning of the experiment the daily control of [CO_2] was unstable, showing large variability in [CO_2] (Fig. 5). This could be related to weak vertical mixing of air (absence of turbulence) due to the smooth surface of wetland floor when reed plants in FACE rings were small. As the plants grew we saw a substantial improvement in the control of [CO_2] with overshoots observed principally during windless periods (Fig. 5).

Short-Term System Performance (Daily)

Daily [CO_2] is shown in Fig. 6 using data from F-1 plot on July 6, 2012. At this point in the growing season, reed plants had grown in average 1.5 m (data not shown), the maximum height achieved during the growing season. On average, [CO_2] oscillated from 566 μmol mol^{-1} during daytime to 1, 143 μmol mol^{-1} in early morning and to 887 μmol mol^{-1}

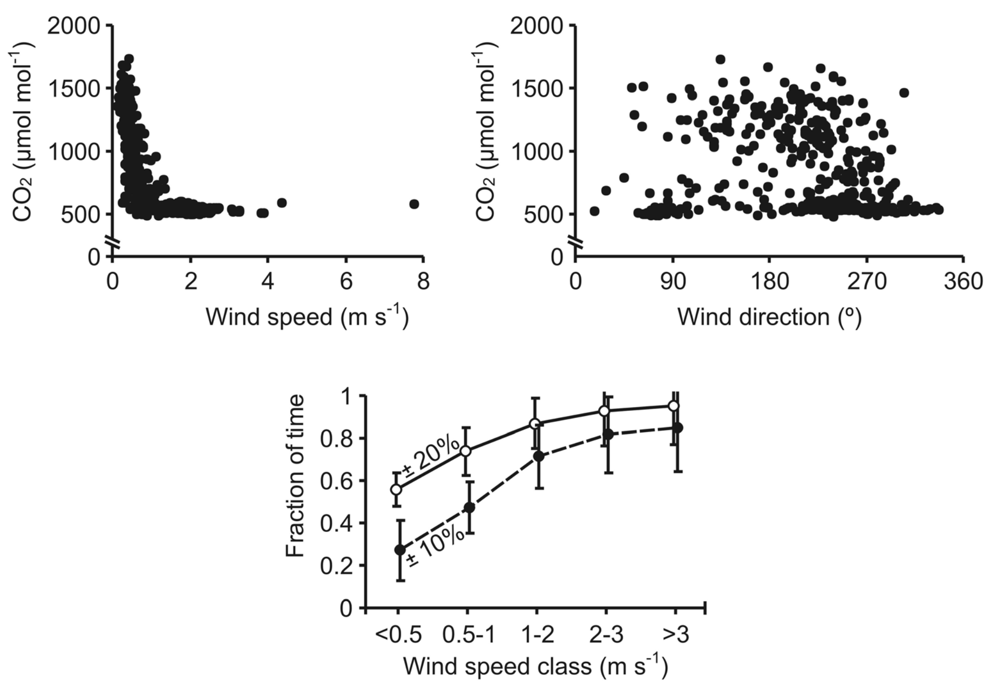


Fig. 4 Dependence of wetland FACE system performance on wind. *Upper panel*: relationships between [CO_2] and wind speed and direction using 1-h averages in July 2012. *Lower panel*: fractions of time in which [CO_2] was within 10 and 20 % of the target (1-min averages) for each wind speed class during the entire season

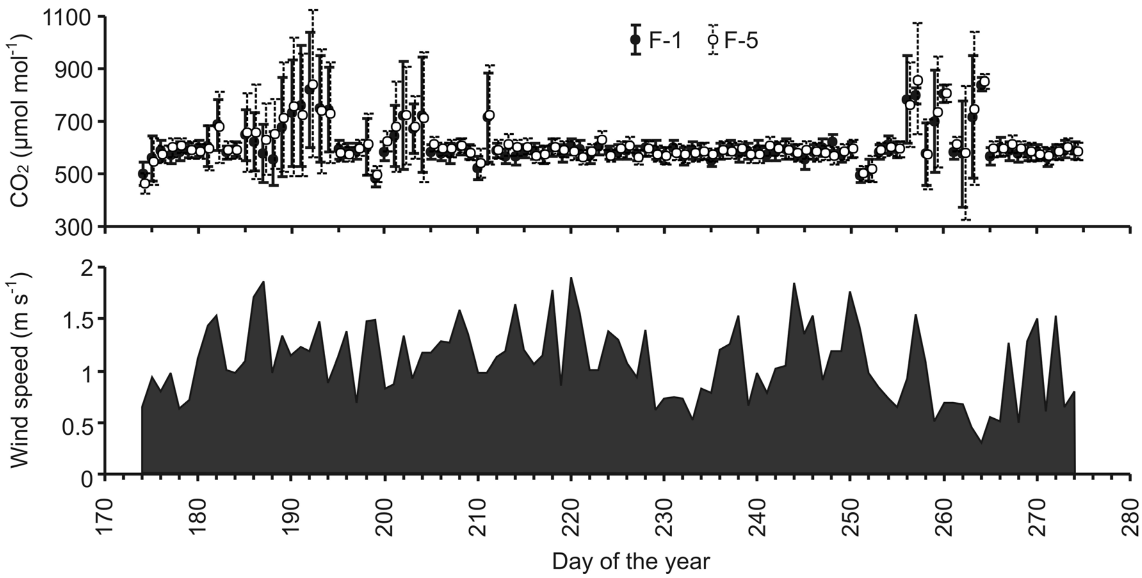


Fig. 5 Time course (24-h averages) of [CO_2] in F-1 and F-5 rings and wind speed in F-3 ring during the experimental period 2012

during the night. Elevated [CO_2] from 1-min records during night time resulted in mean TAR during the entire day of 1.21, ranging from 0.71 to 3.59. The hour of the day was correlated with performance, in response to different atmospheric stability conditions. During midday [CO_2] was within 20 % of the target 100 % of the time. However the control system failed at night, with only 6–45 % of the time showing values within 20 % of the target (4–32 % of the time within 10 % of the target; Fig. 6). The system's ability to control target [CO_2] was correlated with wind speed, air temperature and net radiation (Table 3). FACE system performance has been cited to depend mainly on wind speed and hence on operating mode (i.e., directional control of the CO_2 emission by wind speed and direction; Jordan et al. 1999; Okada et al. 2001). In our wetland FACE, air temperature, wind speed and net radiation were collinear (variance inflation factor=27.2). Forward stepwise multiple regression analyses demonstrated that air temperature was the statistically significant variable that explained the variance of system performance in the short-term (Fraction of time within 20 % of the target=−0.138+0.037*AirTemp (°C), R^2=0.79 p<0.001 AIC=38.5; Fraction of time within 10 % of the target=−0.05+0.023*AirTemp (°C), R^2=0.58 p<0.001 AIC=8.3). According to these statistical analyses, the driving factor of FACE performance was

Fig. 6 Daily record of [CO_2] (at 1-min average), wind speed (at 10-min average) and fractions of time in which [CO_2] was within 10 and 20 % of the target (at hourly intervals) in ring F-5 during July 6th 2012

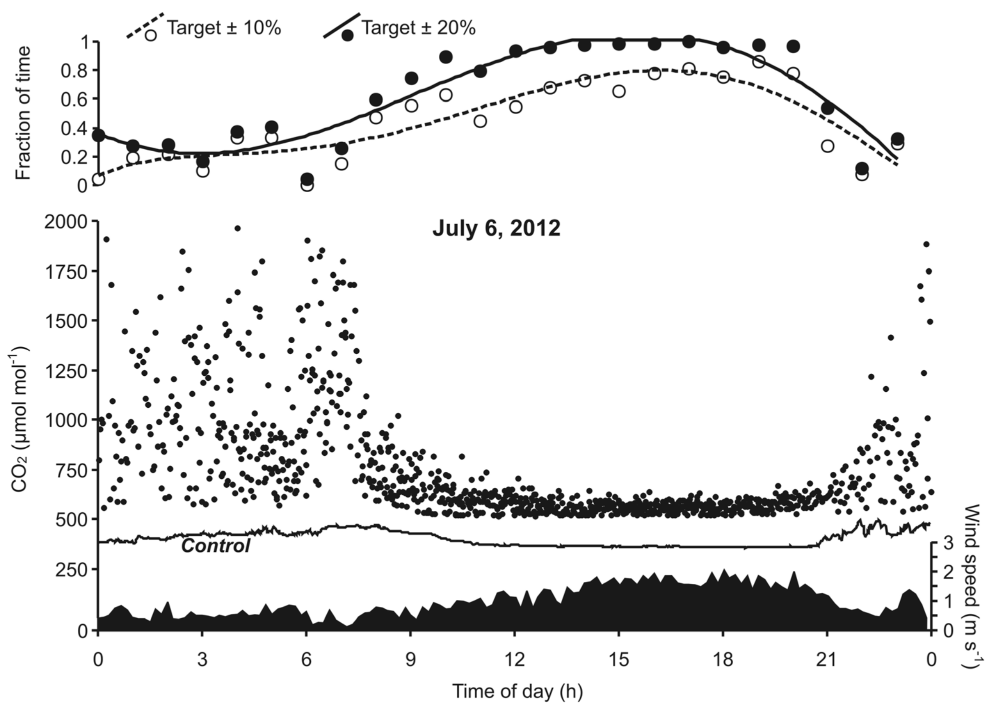


Table 3 Spearman's rank order correlations (r) between the fractions of time in which $[CO_2]$ was within 20 and 10 % of the target (1-min averages) and the environmental variables for a single day (July, 6th 2012) on F-1 ring. All correlations are significant at $p>0.05$

	Fraction of time 20 % TAR	Fraction of time 10 % TAR	Time	Wind speed	Air temperature
Fraction of time 10 % of the target	0.82				
Time (h)	0.54	0.54			
Wind speed (m s^{-1})	0.84	0.76	0.71		
Air temperature (°C)	0.84	0.73	0.64	0.92	
Net radiation (W m^{-2})	0.86	0.70	0.43	0.77	0.88

turbulence: turbulence is caused by the combined effects of temperature, wind speed and net radiation, and has been shown to have a strong effect on FACE performance (Okada et al. 2001; Pepin and Körner 2002). The records at ambient $[CO_2]$ were scarce when the CO_2 enrichment system was not working. The fact that failures to control $[CO_2]$ were almost always positive would indicate that performance may be a controller issue rather than a question of turbulence: the control system could not shut down enough to match demand during low demand periods.

During the entire study period 62 % of FACE ring hourly $[CO_2]$ variance was explained by three environmental variables, through a multiple linear regression: $[CO_2]$=1158–23.1*AirTemp (°C) – 96.7*WindSpeed (m s^{-1})+ 0.8*WindDir (°); R^2 (adjusted)=0.62, Standard Error=176, df=3,2412, $p<0.0001$, AIC=5440.6. Since wind speed and temperature biased $[CO_2]$ response in FACE rings, 89.6 % of the variance in hourly $[CO_2]$ system performance could be described through a Piecewise linear regression with a breakpoint located at $[CO_2]$=689.5 μmol mol^{-1}: $[CO_2]$= 632.0–16.3*WindSpeed (m s^{-1}) – 4.2*AirTemp (°C); AIC= 2728.5 and $[CO_2]$=1300.2–459.6*WindSpeed (m s^{-1}) 1.6*AirTemp (°C); AIC=1827.5.

Spatial Performance and CO_2 Contamination Effects Downwind

Figure 7 shows the interpolated $[CO_2]$ isoconcentrations for ring F-5 over the entire 5 spatial testing days. Contour lines were created using a Kriging method. Since these tests were carried out when there was no plant canopy in the FACE ring plots and to a single height, the extrapolation of results on

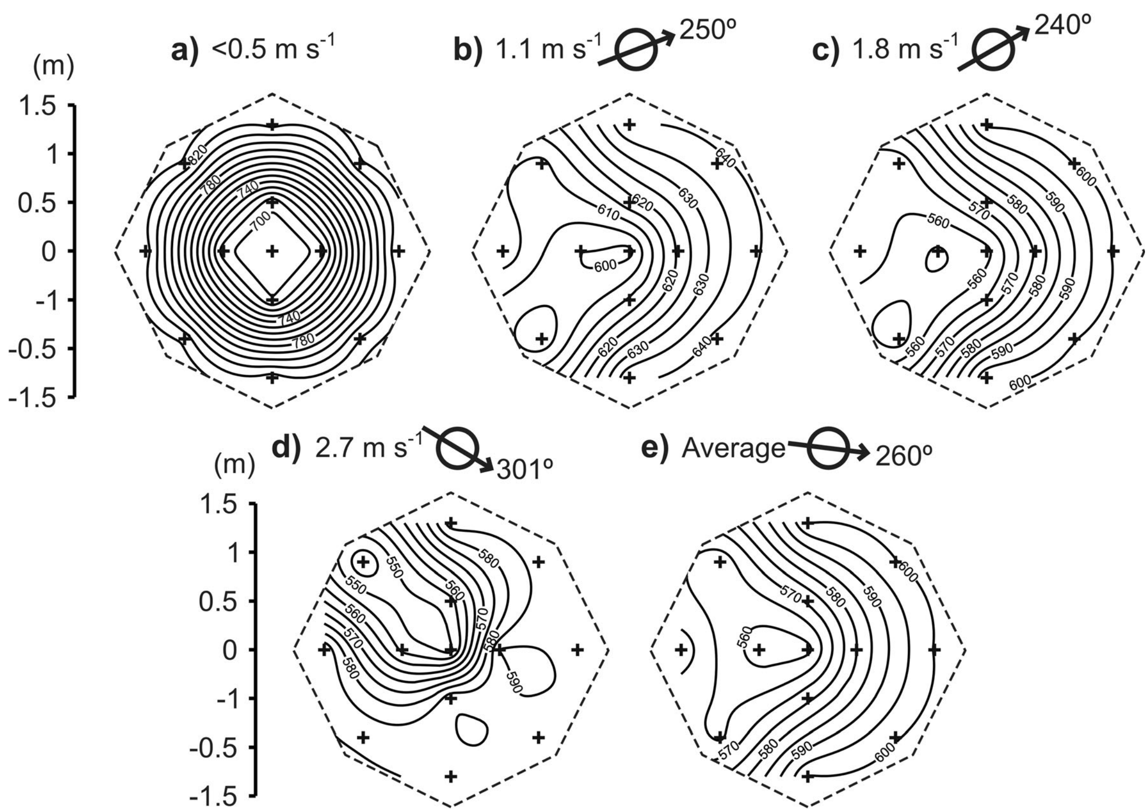
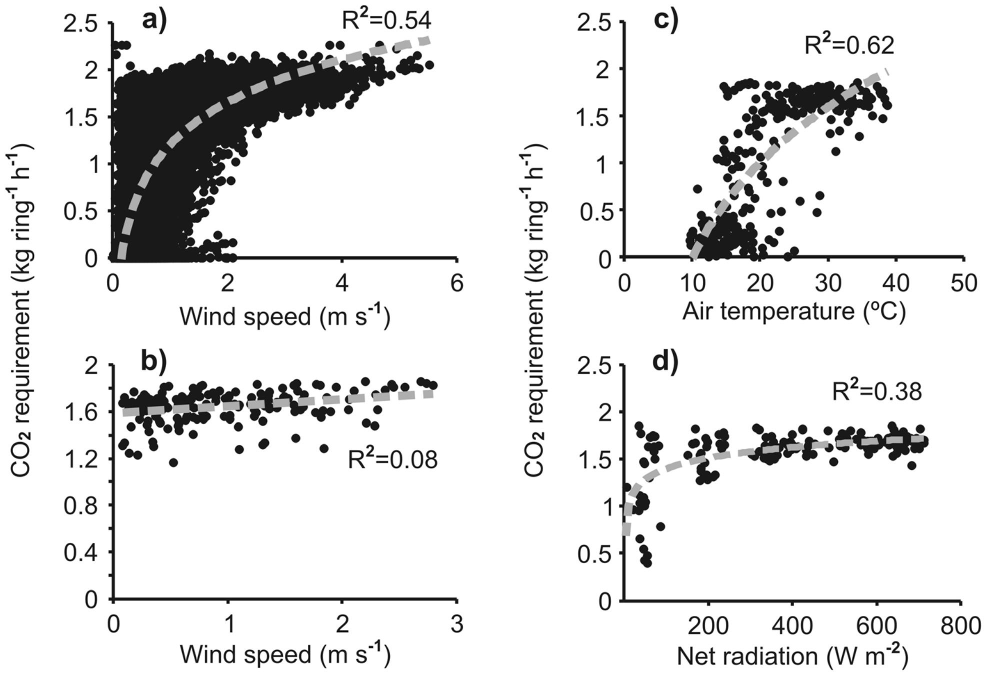


Fig. 7 Spatial distribution of $[CO_2]$ for ring F-5 for different wind conditions experienced during five spatial testing days in 2012

Fig. 8 Mean hourly CO2 requirements per ring as a function of: **a** wind speed using 1-min averages, **b** wind speed using hourly averages, **c** air temperature using hourly averages and **c** net radiation using hourly averages (excluding values lower than 1 W m-2)



system performance when the plant canopy is established would need to be conducted. Since plants occupy a 3D space, not just a 2D area, moving the sampling plane higher or lower would be expected to alter the readings and result in more spatial variability. No significant gradients were detectable across the ring, as the mean differences between each sampling point and the centre of the FACE plot did not exceed 10 % in all wind classes except under calm wind episodes. In the latter case, an excess of CO_2 was recorded (25–55 % of the TAR; Fig. 7a). In most parts of the ring [CO_2] was within the 20 % of TAR when wind speed was equal to its mean value for the whole study period (Fig. 7b). Slight increases in wind speed improved system's performance as [CO_2] was within 10 % of TAR in the whole FACE ring (Fig. 7c). Higher wind speed did not further improve spatial performance, but the [CO_2] value measured at the centre of the ring was closer to the target: e.g., for wind speed=1.1 m s^{-1} [CO_2]=598.4 μmol mol^{-1}, wind speed=1.8 m s^{-1} [CO_2]=558.5 μmol mol^{-1}, and wind speed=2.7 m s^{-1} [CO_2]=547.5 μmol mol^{-1} (Fig. 7d). Across all wind speed classes experienced and within ring centre average [CO_2] (equal to 558.6 μmol mol^{-1}), the [CO_2] spatial distribution within the FACE plot had an eastward overshoot, with differences lower than 10 % TAR (Fig. 7e). During windy episodes a steep gradient of [CO_2] was observed along wind direction (Fig. 7b-e) as cited in other small FACE facilities (Miglietta et al. 2001b). Under low wind speed (<0.5 m s^{-1}) spatial [CO_2] pattern displayed a bowl-shaped distribution, with large differences between the centre of the ring and the periphery (135 μmol mol^{-1}; Fig. 7a). This spatial pattern was related with the circular emission of CO_2 under calm periods as observed in rice FACE plots (Okada et al. 2001). In Okada's facility, during windless periods, the difference in spatial [CO_2] was similar (120 μmol mol^{-1}) although CO_2 was released from sets of four alternating tubes. In our case, [CO_2] excess under calm periods can also be related with the small ring dimensions (half the size of the rice FACE rings). An intermittent CO_2 release during windless periods could help reduce [CO_2] (Okada et al. 2001), but was not implemented during this stage. Usually, small rings display lower [CO_2] spatial variability than larger rings (Hendrey et al. 1999; Miglietta et al. 2001b; Pepin and Körner 2002). Moreover, vertical vent pipes or multiple horizontal pipes are commonly used to improve air mixing and spatial uniformity (Miglietta et al. 2001b; Okada et al. 2001). Also, increasing the large distance between the release point and the canopy volume being studied (allowing Gaussian and turbulent mixing) may provide a more vertically uniform plume. The constraints imposed by our goals (low-cost and simple structure) discouraged these additions, though modifications to our design could be implemented to improve FACE performance.

In control plots, [CO_2] did not increase significantly due to downwind CO_2 contamination effects (Wilcoxon matched paired test p=0.35). Daily mean [CO_2] in control plots was slightly higher in days without fertilization than in fertilized days (388 and 384 μmol mol^{-1}, respectively), although daily mean wind speed was identical (1.9 m s^{-1}). In control plots [CO_2] strongly depended on wind speed, for both fertilized and non fertilized days (R^2=0.82 and 0.76 at p<0.05, respectively). Slight increases in control plot [CO_2] during night time (10–17 μmol mol^{-1}) were observed in both fertilized and non fertilized days, correlated with nocturnal windless episodes (<1 m s^{-1}) associated with atmospheric stability and respiration. Even using the arbitrary contamination events, as cited by Jordan et al. (1999) and defined as instantaneous [CO_2] in a control ring exceeding 110 % of [CO_2] in days without enrichment (388 μmol mol^{-1}*1.1=427 μmol mol^{-1}), these events were uncommon (daytime: 0.1 %, night: 0.7 %) and generally limited to stable nocturnal periods.

CO_2 Requirements

Liquefied carbon dioxide is in general a major cost for FACE facilities, and thus CO_2 use was minimised in order to increase the number of replicates. Across the entire season, an average of 17.4 kg CO_2 $ring^{-1}$ day^{-1} were required to maintain a mean [CO_2] of 582 μmol mol^{-1} in wetland plots. The highest and lowest CO_2 supply levels for a day reached 39 and 6 kg CO_2 $ring^{-1}$ day^{-1}, respectively. Our requirements—on average 2.5 kg CO_2 m^{-2} day^{-1}—were very low compared to other FACE systems. For instance, the rice FACE needed on average around 7 kg CO_2 m^{-2} day^{-1} (Okada et al. 2001) and the MiniFACE from the BERI project required 6 kg CO_2 m^{-2} day^{-1} to maintain a similar target [CO_2] (Miglietta et al. 2001b). Differences between sites were mainly attributed to wind speed and atmospheric stability (Nagy et al. 1992). For example, the rice FACE site experienced calm conditions during 50 % of the experimental season (Okada et al. 2001). Although our experiment required less CO_2 than other similar FACE experiments, other aspects such as the need for a border around the plot for gas mixing and separation of the studied plants from the infrastructure and walkways and the vertical uniformity must be revised in future studies to improve our design and combine the highest performance of FACE technology with the lowest cost possible.

For our wetland FACE rings, there were significant correlations between CO_2 requirements and wind speed, air temperature and net radiation, at different temporal scales (Fig. 8). Using 1-min averages, the rate of ring CO_2 use depended on wind speed through a logarithmic function (CO_2 requirement (kg CO_2 $ring^{-1}$ h^{-1})=0.15*Ln (Wind speed (m s^{-1}))+1.67). However, on an hourly scale, CO_2 use was significantly correlated with those variables influencing atmospheric stability, such as air temperature (CO_2 requirement (kg CO_2 $ring^{-1}$ h^{-1})=1.46*Ln (Air temp (°C))+3.39) and net radiation (excluding values lower than 1 W m^{-2}, CO_2 requirement (kg CO_2 $ring^{-1}$ h^{-1})=1.36*Ln (Net radiation (W m^{-2}))+0.64). This over-enrichment under low-wind conditions may be a reason for the lack of correlation between CO_2 requirements and wind speed (Okada et al. 2001). This implies a need for improved efficiency of the FACE system in terms of CO_2 usage.

Acknowledgments The DECAMERON project (2008/001) funded by the Agency for National Parks of the Spanish Ministry of Agriculture, Food and Environment, provided financial support for the wetland FACE facility. Carburos Metálicos SA sponsored this research and we are very grateful for their important support. Many thanks to TDNP staff, especially to the Principal, Carlos Ruiz de la Hermosa and TRAGSA team for logistic and technical support. We thank to Dr Franco Miglietta for his advice on the facility design and to Dr Magdalena Ferrán Aranaz for her support in implementing the Sheaf Methodology. We would like to thank two anonymous reviewers for their helpful comments on an earlier version of this manuscript. Fabiola Barraclough (Interglobe Language Links) checked the English language. RM was a FPI fellowship; LSG and RSA were supported by JAE-PreDoc and JAE-Doc contracts respectively co-funded by the European Social Funds.

References

Alvarez-Cobelas M, Cirujano S (2007) Multilevel responses of emergent vegetation to environmental factors in a semiarid floodplain. Aquatic Botany 87:49–60

Arp WJ, Drake BG, Pockman WT, Curtis PS, Whigham DF (1993) Interactions between C3 and C4 salt marsh plant species during four years of exposure to elevated atmospheric CO_2. Vegetation 104(105):133–143

Burnham KP, Anderson DR (2002) Model selection and multimodel inference. A practical information-theoretic approach, 2nd edn. Springer, New York

Calfapietra C, Ainsworth EA, Beier C, De Angelis P, Ellsworth DS, Godbold DL, Hendrey GR, Hickler T, Hoosbeek MR, Karnosky DF, King J, Körner C, Leakey ADB, Lewin KF, Liberloo M, Long SP, Lukac M, Matyssek R, Miglietta F, Nagy J, Norby RJ, Oren R, Percy KE, Rogers A, ScarasciaMugnozza G, Stitt M, Taylor G, Ceulemans R (2010) Challenges in elevated CO_2 experiments on forests. Trends in Plant Science 15:5–10

De Graaff MA, van Groenigen KJ, Six J, Hungate B, van Kessel C (2006) Interactions between plant growth and soil nutrient cycling under elevated CO2: a meta-analysis. Global Change Biology 12:2077–2091

Ferrán-Aranaz M (2013) El haz de rectas para la comparación gráfica de series temporales geográficas (in Spanish). Estadística Española 55: 123–148

Guo J, Zhang W, Zhang M, Zhang L, Bian X (2012) Will elevated CO_2 enhance mineral bioavailability in wetland ecosystems? Evidence from a rice ecosystem. Plant and Soil 355:251–263

Harper LA, Baker DN, Box JejrHesketh JD (1973) Carbon dioxide and the photosynthesis of field crops: a metered carbon dioxide release in cotton under field conditions. Agronomy Journal 65:7–11

He Y, Yang X, Miller DR, Hendrey GR, Lewin KF, Nagy J (1996) Effects of FACE systems operation on the micrometeorology of a loblolly pine stand. Transactions of ASAE 39:1551–1556

Hendrey G (1994) The FACE program. Agricultural and Forest Meteorology 70:3–14

Hendrey GR, Kimball BA (1994) The FACE program. Agricultural and Forest Meteorology 70:3–14

Hendrey GR, Ellsworth DS, Lewin KF, Nagy J (1999) A free-air enrichment system for exposing tall forest vegetation to elevated atmospheric CO_2. Global Change Biology 5:293–309

Hoosbeek MR, van Breemen N, Berendse F, Grosvernier P, Vasander H, Wallen B (2001) Limited effect of increased atmospheric CO_2 concentration on ombrotrophic bog vegetation. New Phytologist 150:459–463

IPCC (2007) Summary for policymakers. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller

HL (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Jongen M, Jones MB, Hebeisen T, Blum H, Hendrey G (1995) The effects of elevated CO_2 concentrations on the root growth of *Loliumperenne* and *Trifoliumrepens* grown in a FACE system. Global Change Biology 1:361–371

Jordan D, Zitzer SF, Hendrey GR, Lewin KF, Nagy J, Nowak RS, Smith SD, Coleman JS, Seemann JR (1999) Biotic, abiotic and performance aspects of the Nevada Desert Free-Air CO_2 Enrichment (FACE) Facility. Global Change Biology 5:659–668

Kimball BA, Pinter PJ, Garcia RL, LaMorte RL, Wall GW, Hunsaker DJ, Wechsung G, Wechsung F, Kartschall T (1995) Productivity and water use of wheat under free air CO_2 enrichment. Global Change Biology 1:429–442

Kimball BA, Pinter PJ, Wall GW, Garcia RL, LaMorte RL, Jak PMC, Frumau KFA, Vugts HF (1997) Comparisons of responses of vegetation to elevated carbon dioxide in free-air and open-top chamber facilities. Advances in Carbon Dioxide Effects Research. ASA Special Publication no. 61, pp. 113-130

Lewin KF, Hendrey G, Kolber Z (1992) Brookhaven national laboratory free-air carbon dioxide enrichment facility. Critical Reviews in Plant Sciences 11:135–141

Lewin KF, Hendrey G, Nagy J, LaMorte RL (1994) Design and application of a free-air carbon dioxide enrichment facility. Agricultural and Forest Meteorology 70:15–29

Lewin KF, Nagy J, Nettles WR, Cooley DM, Rogers A (2009) Comparison of gas use efficiency and treatment uniformity in a forest ecosystem exposed to elevated [CO_2] using pure and prediluted free air CO2 enrichment technology. Global Change Biology 15:388–395

McLeod AR, Long SP (1999) Free-air carbon dioxide enrichment (FACE) in global change research; a review. Advances in Ecological Research 28:1–56

Miglietta F, Giuntoli A, Bindi M (1996) The effect of Free Air Carbon Dioxide Enrichment (FACE) and soil nitrogen availability on the photosynthetic capacity of wheat. Photosynthesis Research 47:281–290

Miglietta F, Lanini M, Bindi M, Magliulo V (1997) Free air CO_2 enrichment of potato (*Solanumtuberosum* L.): design and performance of the CO_2-fumigation system. Global Change Biology 3:417–427

Miglietta F, Hoosbeek MR, Foot J, Gigon F, Hassinen A, Heijmans M, Peressotti A, Saarinen T, Van Breemen N, Wallén B (2001a) Spatial and temporal performance of the MINIFACE (Free air CO_2 enrichment) system on bog ecosystems in northern and central Europe. Environmental Monitoring and Assessment 66:107–127

Miglietta F, Peressotti A, Vaccari FP, Zaldei A, deAngelis P, Scarascia-Mugnozza G (2001b) Free-air CO_2 enrichment (FACE) of a poplar plantation: the POPFACE fumigation system. New Phytologist 150: 465–476

Mozdzer TJ, Megonigal JP (2012) Jack-and-master trait responses to elevated CO and N: a comparison of native and introduced *Phragmites australis*. PLoS ONE 7:e42794

Nagy J, Lewin KF, Hendrey GR, Lipfert FW, Daum ML (1992) FACE facility engineering performance in 1989. Critical Reviews in Plant Sciences 11:165–185

Neter J, Kutner MH, Nachtsheim CJ (1996) Applied linear statistical models. McGraw-Hill, Boston

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

Ortiz-Llorente MJ (2013) Drought and CO_2 cycling: response of emergent plants in a wetland (In Spanish). PhD Thesis, Facultad de Biología, Universidad Complutense de Madrid. (http://eprints.ucm.es/24587/1/T35170.pdf)

Pepin S, Körner C (2002) Web-FACE: a new canopy free-air CO2 enrichment system for tall trees in mature forests. Oecologia 133: 1–9

Rasse D, Peresta G, Drake BG (2005) Seventeen years of elevated CO2 exposure in a Chesapeake Bay Wetland: sustained but contrasting responses of plant growth and CO_2 uptake. Global Change Biology 11:369–377

Rodríguez-Murillo JC, Almendros G, Knicker H (2011) Wetland soil organic matter composition in a Mediterranean semiarid wetland (Las Tablas de Daimiel, Central Spain): insight into different carbon sequestration pathways. Organic Geochemistry 42:762–773

Sánchez-Carrillo S, Álvarez-Cobelas M (2010) Climate and hydrologic trends: climate change versus hydrologic overexploitation as determinants of the fluctuating wetland hydrology. In: Sánchez-Carrillo S, Angeler DG (eds) Ecology of threatened semi-arid wetlands: long-term research in Las Tablas de Daimiel. Springer, Berlin, pp 45–83

Sánchez-Carrillo S, Angeler DG (eds) (2010) Ecology of threatened semi-arid wetlands: long-term research in Las Tablas de Daimiel. Springer, Berlin

Solomon S, Qin D, Manning M, Alley RB, Berntsen T, Bindoff NL, Chen Z, Chidthaisong A, Gregory JM, Hegerl GC, Heimann M, Hewitson B, Hoskins BJ, Joos F, Jouzel J, Kattsov V, Lohmann U, Matsuno T, Molina M, Nicholls N, Overpeck J, Raga G, Ramaswamy V, Ren J, Rusticucci M, Somerville R, Stocker TF, Whetton P, Wood RA, Wratt D (2007) Technical summary. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis contribution of working group i to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 25–77

Zar JH (1999) Biostatistical analysis, 4th edn. Pearson, Upper Saddle River

Ziska LH, Drake BG, Chamberlain S (1990) Long-term photosynthetic response in single leaves of A C3 and C4 salt marsh species grown at elevated atmospheric CO_2 in situ. Oecologia 83:469–472