1 A Free Air CO₂ Enrichment (FACE) Facility in a Wetland
2 to Study the Effects of Elevated Atmospheric Carbon
3 Dioxide: System Description and Performance

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Abstract The Free Air CO₂ Enrichment (FACE) system has proved suitable for exposing plants to elevated [CO₂] 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 *Phragmites australis* was grown. The target [CO₂] was 550 μmol mol⁻¹ and fertilization was carried out continuously. Daily temporal [CO₂] performance was adequate with 61% and 83% of air samples at the ring's centre having a [CO₂] within 10% and 20% of the target, respectively, with values closest to their target during summer months and daytime. Spatial [CO₂] distribution showed no significant gradients across the ring. Increased wind speed improved the system's spatial performance, as [CO₂] was within ±10% of the target in the whole ring. Across the entire fertilization season, CO₂ requirements for maintaining a mean [CO₂] of 582 μmol mol⁻¹ in wetland plots averaged 17.4 kg CO₂ ring⁻¹ day⁻¹. Our requirements (2.5 kg CO₂ m⁻² day⁻¹) were very low compared to other FACE systems, demonstrating its high potential to study the effects of elevated CO₂ in wetlands at low cost.

Keywords: elevated carbon dioxide, free-air CO₂ enrichment (FACE), performance control, design, wetland.

49 Introduction

50 The increase of atmospheric [CO₂] from pre-industrial times is amongst
51 the most significant impacts of human activity on global climate (IPCC
52 2007; Solomon et al. 2007). One of the main challenges facing research
53 into elevated [CO₂] effects on ecosystems and vegetation is the
54 simulation of high [CO₂] levels without changing the physical
55 environment of growing vegetation. Free Air CO₂ Enrichment (FACE)
56 systems have proven suitable to expose plants to elevated [CO₂] with
57 minimal disturbance of their natural environment (solar radiation,
58 temperature, humidity and wind) which can influence their response to
59 elevated [CO₂] (McLeod and Long 1999). FACE has been successfully used
60 since the late 1980s to expose agricultural crops, grasslands, forest
61 plantations and desert shrubs to elevated [CO₂] (Hendrey 1994; Kimball
62 et al. 1995; Jongen et al. 1995; Miglietta et al. 1997; see Okada et
63 al. 2001 for a further explanation of FACE advantages). However,
64 although FACE can be considered superior to other CO₂ exposure
65 techniques, most studies in wetlands have been performed using the
66 open-top chamber technique (e.g. Ziska et al. 1990; Arp et al. 1993;
67 Rasse et al. 2005). Although differences between both open-top
68 chambers and FACE are not conclusive, in some cases the environment
69 inside the chamber can induce greater plant growth and the FACE
70 approach is preferred for many studies because both absolute and
71 relative responses to elevated CO₂ can be reliably obtained (Kimball
72 et al. 1997; De Graaf et al. 2006). In fact, FACE technology was
73 developed in order to expose whole-ecosystems to elevated CO₂
74 (Calfapietra et al. 2010) and to avoid chamber effects on microclimate

75 (Hendrey et al. 1994; Miglietta et al. 2001a). FACE has only been
76 implemented to account for wetlands such as boreal peatlands (bogs;
77 Hoosbeek et al. 2001; Miglietta et al. 2001b) and rice ecosystems
78 (Okada et al. 2001; Guo et al. 2012), but not to date in marshes which
79 require some technological adjustments to account for emergent
80 vegetation and higher water levels.

81 FACE technology has developed considerably since the first experiments
82 carried out in 1970s (Harper et al. 1973; Lewin et al. 1992).
83 Typically, FACE systems consist of a circular structure (commonly
84 referred to as a ring) constructed from pipes (vertical or horizontal)
85 that surround the vegetation. These pipes emit CO₂ in order to obtain
86 a zone with higher [CO₂] than the surrounding ambient atmosphere.
87 Generally speaking, tall vegetation requires large rings with
88 multilevel (vertical) emission pipes; whereas small rings with
89 emission pipes located at a single height may be adequate for short
90 vegetation, although it depends on the environment and conditions
91 where the experiment is performed. The main limitations of traditional
92 FACE systems are the major capital expenditure they entail, the
93 complex CO₂ emission structures, the amount of gas required to obtain
94 a prolonged exposure to elevated CO₂, and the local environment
95 constraints. Moreover, the use of blowers or fans to predilute and
96 evenly mix the injected CO₂ with ambient air has high power
97 requirements and requires significant infrastructure. Notwithstanding,
98 the use of fans during periods with low wind speeds has been shown to
99 conserve enough CO₂ to recover the infrastructure costs in a FACE
100 experiment performed in a forest (Lewin et al. 2009). Under some

101 conditions, fans can perturb the micro-meteorological conditions
102 inside the ring thus affecting atmospheric stability (He et al. 1996,
103 Okada et al. 2001). The release of pure CO₂ instead of an air-CO₂
104 mixture has been shown to be a reliable alternative to conventional
105 systems, having been used successfully in different locations (Okada
106 et al. 2001; Miglietta et al. 2001a and 2001b). Pure CO₂ is emitted at
107 high pressure and velocity, through a large number of tiny holes (gas
108 jets). Therefore a quick and efficient mixing of CO₂ inside the ring
109 is obtained, according to the theory of fluid mechanics (Miglietta et
110 al. 2001a). FACE facilities installed in marshlands, peatbogs or rice
111 paddy fields (also in other irrigated crops) must be designed for
112 environmental conditions that include the periodic inundation of
113 soils. The ring structures and emission pipes must be able to
114 withstand periodic inundation and the equipment must be adapted to
115 operate under high humidity conditions.

116 We know of no previous study using FACE facilities to investigate the
117 effects of high [CO₂] in wetlands. Although one study evaluated the
118 effects of elevated [CO₂] under greenhouse conditions on the common
119 reed *Phragmites australis* (Mozdzer and Megonigal 2012), there are no
120 studies assessing the response of *P. australis* to elevated [CO₂] under
121 field conditions. It is important to assess the effects of predicted
122 increases in atmospheric [CO₂] on wetland ecosystem function and
123 structure. This will allow us to predict the extent to which these
124 changes could affect their capacity to provide numerous environmental
125 services, including global change mitigation. The SAWFACE (Semi-Arid
126 Wetland FACE) project is the first experiment to grow reed under

127 elevated [CO₂] without using enclosures. It started in 2009, with
128 design trials carried out in 2010-11. The FACE facility was set up in
129 2012 with a second year of enrichment being carried out in 2013. Here
130 we describe in detail the design and construction of the FACE facility
131 and the system's performance during the 2012 growing season (May-
132 September).

133

134 **Material and methods**

135 *Site description*

136 Las Tablas de Daimiel National Park (TDNP) is a semiarid floodplain
137 wetland located in central Spain (39°08'N, 3°43'W). The maximum
138 inundated area is 16 km² with an average water depth of 0.90 m. TDNP
139 is situated at the outlet of a 13,000 km² catchment that overlays a
140 5000 km² aquifer. The wetland's hydrology is currently fluctuating,
141 with long drought periods associated with groundwater overexploitation
142 by irrigation practices (Sánchez-Carrillo and Álvarez-Cobelas 2010).
143 From 2004 to 2009 the wetland experienced one of the greatest droughts
144 of the last 50 years, and peat fire threatened to destroy the entire
145 wetland. Subsequently (2010-2014) the ecosystem experienced highest
146 mean annual water level in the last 30 years. The Gigüela River is the
147 only water input to TDNP, although from 2012 groundwater levels are
148 rising and some springs are also feeding the wetland.

149 The soils of TDNP are slightly saline SO₄-rich histosols, and many
150 areas have high organic matter content. The soil is mainly dominated
151 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 ($\approx 900 \text{ m}^2$) 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 $[\text{CO}_2]$ (Fig1). FACE and control rings were distributed randomly in the experimental area maintaining a distance greater than 6 meters 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 ($\approx 7 \text{ m}^2/\text{plot}$) and

177 consisted of eight 1.2-m long polyethylene pipes (emission pipes) with
178 a diameter of 16 mm (thickness of 0.5 mm) arranged to make an octagon
179 (Fig. 2a). Each emission pipe was suspended horizontally at 20-30 cm
180 above the macrophyte canopy, using eight stainless steel poles (4-m of
181 height) located at the vertices of an octagon. These were assembled at
182 the top with a detachable steel structure also forming an octagon. The
183 lower part of the poles was welded to flat stainless steel plates,
184 which were attached to the wetland soil using perforated concrete
185 blocks. This increased the octagon structure's stability during
186 flooding. The height of the emission tubes was regulated weekly
187 according to vegetation height during its growth cycle by using
188 stainless steel chains which were attached to the upper octagon
189 structure (Fig. 2a).

190 The gas used for enrichment was liquefied ultrapure CO₂ stored in a
191 VT21 tank (≈40,000 kg), located outside the wetland (~400 m distance).
192 Liquid CO₂ was supplied to electrical heat exchangers which vaporized
193 it. The resulting CO₂ gas was channelled to a pressure regulator that
194 reduced line pressure to 500-1,000 kPa. Finally CO₂ gas was piped to
195 FACE plots through 16-mm diameter polyamide tubing which was buried to
196 minimize the risk of damage.

197 FACE rings were based on directionally controlled release of pure CO₂
198 from jets (micro-holes) located in the emission pipes. By releasing
199 CO₂ through the jets the gas reaches sonic velocity so that,
200 consistent with the theory of fluid mechanics, it creates a shock wave
201 at the outlet and substantially improves mixing with air (Miglietta et
202 al. 2001a). The reason for using micro-holes is to obtain a rapid

mixing between CO₂ and air, which achieves a significant simplification of construction and reduced capital cost of the FACE facility. The study of Miglietta et al. (2001a) stated that such dilution is almost independent of the absolute CO₂ 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 CO₂ 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 CO₂ 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 [CO₂] 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 $< 0.5 \text{ m s}^{-1}$), 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.).

256 *FACE facility control and operation*

257 The operation of the FACE system was carried out from a casing control
258 cabin (Fig. 2b). All equipment and various circuits operating at 12 V
259 and 24 V DC were installed and connected to a laptop computer, which
260 ran the facility. Power supply to the FACE facility was provided by
261 solar panels (700 W) and rechargeable gel batteries, to avoid any
262 damage by lightning. Measurements obtained by the IRGA located at plot
263 FACE-1 were used for the operation of F-1, F-2, F-3 and F-4 plots,
264 whereas those recorded by the IRGA in FACE-5 were computed for the
265 [CO₂] control of F-5 and F-6 plots. Since data from wind sensors
266 located at FACE-3 and FACE-5 plots were very similar (see results
267 section), the use of records to compute CO₂ emissions of remaining
268 plots was established randomly (FACE-3: F-1, F-2, F-3 and F-4; FACE 5:
269 F-5 and F-6).

270 All variables were processed by means of a proportional integral
271 differential (PID) algorithm programmed in Visual Basic (Microsoft®).
272 The PID algorithm was a modified version of that described by Lewin et
273 al. (1994) with discrete time signals. The PID-type algorithm
274 calculates the voltage provided to the pressure regulator, which
275 controls the pressure of CO₂ released into the FACE rings, according
276 to the [CO₂] reached in the previous time interval and a target [CO₂]
277 value. The PID algorithm regulated the CO₂ flow into the rings until
278 the proposed target level was reached. The selected target [CO₂] was
279 550 $\mu\text{mol mol}^{-1}$. Briefly, the output signal to the CO₂ flow controller
280 (F_{tot}) depends on the integral (F_{int}), proportional (F_{prop}) and
281 differential (F_{diff}) CO₂ 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 $[\text{CO}_2]$ 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 $< 0.5 \text{ m s}^{-1}$ 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

307 equipment maintenance or malfunction. Because the aim of this
308 experiment was to test the effects of CO₂ enrichment on wetland as a
309 system, half of both FACE and Control plots were kept unvegetated
310 during the fertilization by means of clipping new shoots of reed
311 weekly. Clearly, no soil process is directly affected by elevated CO₂
312 alone; however, some soil processes can be affected indirectly by
313 means of vegetation responses to elevated CO₂ in the root zone.
314 Therefore in order to distinguish these effects, half the plots were
315 kept free of vegetation.

316 Temporal performance was assessed using 1 min average [CO₂] measured
317 at the centre of FACE and control rings. Since a CO₂ concentration
318 gradient along wind direction is unavoidable within a FACE ring
319 (Miglietta et al. 1996), spatial performance was determined as the
320 difference between the [CO₂] measured at canopy height in the centre
321 of the ring and [CO₂] measured at any other point of the ring at the
322 same height. For this purpose, during 5 non-consecutive days (mid-
323 March 2012), a manually operated multiport gas sampler connected to an
324 IRGA (WMA-4 PP-Systems) was used to take air samples in 12 sampling
325 points, evenly spaced within the FACE plot F-5 at canopy height. Tests
326 were done from 07:00 to 21:00 h with two observations taken during
327 night (22:00-01:00 h). Because at the time of this test no plants grew
328 in FACE rings, a height of 1.5 m was assumed to be representative of
329 the mean reed height in the wetland. As IRGA measurements of [CO₂] are
330 taken during 1.6 s, every 5 seconds a measurement was taken at each
331 sampling point (1 record per sampling site per minute; 5 x 12 = 60).
332 Simultaneously [CO₂] was sampled at the same frequency in the centre

333 of the FACE ring using an additional IRGA. Periodic auto zeros were
334 programmed in both IRGAs, performed every 5 min for providing
335 automatic correction for sample cell contamination, detector
336 sensitivity variations and pre-amplifier gain changes. Throughout the
337 spatial test the both IRGA were cross-calibrated daily.

338 FACE system performance was computed as an assessment of the temporal
339 and spatial control of [CO₂] within the FACE rings, and also as the
340 overall reliability of the FACE system in supplying CO₂ (Okada et al.
341 2001) as follows:

342 *Target achievement ratio (TAR) = FACE / set point*

343 Where *FACE* is the [CO₂] of a sample measured in a FACE ring, *set point*
344 is the [CO₂] target level desired at that time. For a given period or
345 environmental conditions, the fraction of recorded [CO₂] values that
346 were within 10 or 20% of the target were calculated ($0.9 \leq \text{TAR} \leq 1.1$ or
347 $0.8 \leq \text{TAR} \leq 1.2$). These fraction limits were calculated using [CO₂]
348 recorded at the ring centre every 1.6 seconds for 1-min averages, 24-h
349 averages, as well daytime and night time averages. These data were
350 recorded for both the entire observational period (from March to
351 October) and the summer months (from July to September).

352 To assess CO₂ contamination downwind in adjacent control plots the
353 temporal trends of [CO₂] were compared within control plots, between
354 days with similar wind speed pattern, using those days when the FACE
355 system was not in operation, compared with those in operation (without
356 CO₂ enrichment: 28-Apr, 5-May, 4-Jun, 18-Jun, 4-Jul and 6-Aug).
357 Similarity of daily wind speed time-series was assessed using the

358 Sheaf methodology, a graphical method to compare time-series (Ferrán-
359 Aranaz 2013). Pairs of similar wind speed days, used to assess the CO₂
360 contamination effects downwind in control plots, were: April 28th vs
361 May 4th and May 5th vs July 8th. The system's ability to control the
362 target [CO₂] was studied through multiple regressions with
363 environmental variables (air temperature, wind speed and direction,
364 net radiation and time). Collinearity was investigated using the
365 variance inflation factor in multiple regressions (Neter et al. 1996).
366 Adjusted R² was used for assessing goodness of fit to the models (Zar
367 1999) while the comparison was assessed computing the Akaike
368 Information Criterion (AIC), based on information theory (Burnham and
369 Anderson 2002). We also used non-linear estimations (i.e. piecewise
370 linear regression) to compute the effects of single environmental
371 variables on [CO₂].

372

373 **Results and discussion**

374 *Wind and Long-term system performance*

375 Daily mean wind speed ranged from 0.3 to 2.8 m s⁻¹, while the mean wind
376 speed for the whole study period was 1.12±0.87 and 1.18±0.96 m s⁻¹ in
377 F-3 and F-5 rings, respectively. Wind speeds in both rings were quite
378 similar for instantaneous records (R²= 0.94, p<0.01) as well for daily
379 averages (R²= 0.90, p<0.01). 72% of the time, wind speed was above 0.5
380 m s⁻¹ (Fig. 3). Wind speeds above 3 m s⁻¹ were sporadic (Fig. 3). Maximum
381 instantaneous wind speed was recorded during daytime, achieving 35.6 m
382 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 ($550 \mu\text{mol mol}^{-1}$), 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 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 ($550 \mu\text{mol mol}^{-1}$) 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 $[\text{CO}_2]$ 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 25-30% of study period time, and is considered the main cause for the difference in our FACE facility $[\text{CO}_2]$ control performance of $[\text{CO}_2]$ of our facility 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 $[\text{CO}_2]$ was unstable, showing large variability in $[\text{CO}_2]$ (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 $[\text{CO}_2]$ with overshoots observed principally during windless periods (Fig. 5).

Short-term system performance (daily)

Daily $[\text{CO}_2]$ is shown in Figure 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, $[\text{CO}_2]$ oscillated from $566 \mu\text{mol mol}^{-1}$ during daytime to $1,143 \mu\text{mol mol}^{-1}$ in early morning and to $887 \mu\text{mol mol}^{-1}$ during the night. Elevated $[\text{CO}_2]$ from 1-min records during night time resulted in mean TAR during the entire day of 1.21, ranging from 0.71

434 to 3.59. The hour of the day was correlated with performance, in
 435 response to different atmospheric stability conditions. During midday
 436 [CO₂] was within 20% of the target 100% of the time. However the
 437 control system failed at night, with only 6-45% of the time showing
 438 values within 20% of the target (4-32% of the time within 10% of the
 439 target; Fig. 6). The system's ability to control target [CO₂] was
 440 correlated with wind speed, air temperature and net radiation (Table
 441 3). FACE system performance has been cited to depend mainly on wind
 442 speed and hence on operating mode (i.e. directional control of the CO₂
 443 emission by wind speed and direction; Jordan et al. 1999; Okada et al.
 444 2001). In our wetland FACE, air temperature, wind speed and net
 445 radiation were collinear (variance inflation factor= 27.2). Forward
 446 stepwise multiple regression analyses demonstrated that air
 447 temperature was the statistically significant variable that explained
 448 the variance of system performance in the short-term (Fraction of time
 449 within 20% of the target= $-0.138 + 0.037 \cdot \text{AirTemp}(^{\circ}\text{C})$, $R^2 = 0.79$ $p < 0.001$
 450 $\text{AIC} = 38.5$; Fraction of time within 10% of the target= $-0.05 +$
 451 $0.023 \cdot \text{AirTemp}(^{\circ}\text{C})$, $R^2 = 0.58$ $p < 0.001$ $\text{AIC} = 8.3$). According to these
 452 statistical analyses, the driving factor of FACE performance was
 453 turbulence: turbulence is caused by the combined effects of
 454 temperature, wind speed and net radiation, and has been shown to have
 455 a strong effect on FACE performance (Okada et al. 2001, Pepin and
 456 Körner 2002). The records at ambient [CO₂] were scarce when the CO₂
 457 enrichment system was not working. The fact that failures to control
 458 [CO₂] were almost always positive would indicate that performance may
 459 be a controller issue rather than a question of turbulence: the

460 control system could not shut down enough to match demand during low
461 demand periods.

462 During the entire study period 62% of FACE ring hourly $[CO_2]$ variance
463 was explained by three environmental variables, through a multiple
464 linear regression: $[CO_2] = 1158 - 23.1 * AirTemp(^{\circ}C) - 96.7 * WindSpeed(m\ s^{-1}) + 0.8 * WindDir(^{\circ})$; $R^2(\text{adjusted}) = 0.62$, Standard Error = 176, $df = 3,2412$, $p < 0.0001$, $AIC = 5440.6$. Since wind speed and temperature biased
467 $[CO_2]$ response in FACE rings, 89.6% of the variance in hourly $[CO_2]$
468 system performance could be described through a Piecewise linear
469 regression with a breakpoint located at $[CO_2] = 689.5\ \mu\text{mol mol}^{-1}$: $[CO_2] =$
470 $632.0 - 16.3 * WindSpeed(m\ s^{-1}) - 4.2 * AirTemp(^{\circ}C)$; $AIC = 2728.5$ and $[CO_2] =$
471 $1300.2 - 459.6 * WindSpeed(m\ s^{-1}) - 1.6 * AirTemp(^{\circ}C)$; $AIC = 1827.5$.

472

473 *Spatial performance and CO_2 contamination effects downwind*

474 Figure 7 shows the interpolated $[CO_2]$ isoconcentrations for ring F-5
475 over the entire 5 spatial testing days. Contour lines were created
476 using a Kriging method. Since these tests were carried out when there
477 was no plant canopy in the FACE ring plots and to a single height, the
478 extrapolation of results on system performance when the plant canopy
479 is established would need to be conducted. Since plants occupy a 3D
480 space, not just a 2D area, moving the sampling plane higher or lower
481 would be expected to alter the readings and result in more spatial
482 variability. No significant gradients were detectable across the ring,
483 as the mean differences between each sampling point and the centre of
484 the FACE plot did not exceed 10% in all wind classes except under calm

485 wind episodes. In the latter case, an excess of CO₂ was recorded (25-
 486 55% of the TAR; Fig. 7a). In most parts of the ring [CO₂] was within
 487 the 20% of TAR when wind speed was equal to its mean value for the
 488 whole study period (Fig. 7b). Slight increases in wind speed improved
 489 system's performance as [CO₂] was within 10% of TAR in the whole FACE
 490 ring (Fig. 7c). Higher wind speed did not further improve spatial
 491 performance, but the [CO₂] value measured at the centre of the ring
 492 was closer to the target: e.g. for wind speed= 1.1 m s⁻¹ [CO₂]= 598.4
 493 μmol mol⁻¹, wind speed= 1.8 m s⁻¹ [CO₂]= 558.5 μmol mol⁻¹, and wind
 494 speed= 2.7 m s⁻¹ [CO₂]= 547.5 μmol mol⁻¹ (Fig. 7d). Across all wind
 495 speed classes experienced and within ring centre average [CO₂] (equal
 496 to 558.6 μmol mol⁻¹), the [CO₂] spatial distribution within the FACE
 497 plot had an eastward overshoot, with differences lower than 10% TAR
 498 (Fig. 7e). During windy episodes a steep gradient of [CO₂] was
 499 observed along wind direction (Fig. 7b-e) as cited in other small FACE
 500 facilities (Miglietta et al. 2001b). Under low wind speed (<0.5 m s⁻¹)
 501 spatial [CO₂] pattern displayed a bowl-shaped distribution, with large
 502 differences between the centre of the ring and the periphery (135 μmol
 503 mol⁻¹; Fig. 7a). This spatial pattern was related with the circular
 504 emission of CO₂ under calm periods as observed in rice FACE plots
 505 (Okada et al. 2001). In Okada's facility, during windless periods, the
 506 difference in spatial [CO₂] was similar (120 μmol mol⁻¹) although CO₂
 507 was released from sets of four alternating tubes. In our case, [CO₂]
 508 excess under calm periods can also be related with the small ring
 509 dimensions (half the size of the rice FACE rings). An intermittent CO₂
 510 release during windless periods could help reduce [CO₂](Okada et al.
 511 2001), but was not implemented during this stage. Usually, small rings

512 display lower [CO₂] spatial variability than larger rings (Hendrey et
513 al. 1999, Miglietta et al. 2001b, Pepin and Körner 2002). Moreover,
514 vertical vent pipes or multiple horizontal pipes are commonly used to
515 improve air mixing and spatial uniformity (Miglietta et al. 2001b,
516 Okada et al. 2001). Also, increasing the large distance between the
517 release point and the canopy volume being studied (allowing Gaussian
518 and turbulent mixing) may provide a more vertically uniform plume. The
519 constraints imposed by our goals (low-cost and simple structure)
520 discouraged these additions, though modifications to our design could
521 be implemented to improve FACE performance.

522 In control plots, [CO₂] did not increase significantly due to downwind
523 CO₂ contamination effects (Wilcoxon matched paired test $p = 0.35$).
524 Daily mean [CO₂] in control plots was slightly higher in days without
525 fertilization than in fertilized days (388 and 384 $\mu\text{mol mol}^{-1}$,
526 respectively), although daily mean wind speed was identical (1.9 m s^{-1}).
527 In control plots [CO₂] strongly depended on wind speed, for both
528 fertilized and non fertilized days ($R^2 = 0.82$ and 0.76 at $p < 0.05$,
529 respectively). Slight increases in control plot [CO₂] during night
530 time (10-17 $\mu\text{mol mol}^{-1}$) were observed in both fertilized and non
531 fertilized days, correlated with nocturnal windless episodes ($< 1 \text{ m s}^{-1}$)
532 associated with atmospheric stability and respiration. Even using the
533 arbitrary contamination events, as cited by Jordan et al. (1999) and
534 defined as instantaneous [CO₂] in a control ring exceeding 110% of
535 [CO₂] in days without enrichment ($388 \mu\text{mol mol}^{-1} \times 1.1 = 427 \mu\text{mol mol}^{-1}$),
536 these events were uncommon (daytime: 0.1%, night: 0.7%) and generally
537 limited to stable nocturnal periods.

538

539 *CO₂ requirements*

540 Liquefied carbon dioxide is in general a major cost for FACE
541 facilities, and thus CO₂ use was minimised in order to increase the
542 number of replicates. Across the entire season, an average of 17.4 kg
543 CO₂ ring⁻¹ day⁻¹ were required to maintain a mean [CO₂] of 582 µmol mol⁻¹
544 in wetland plots. The highest and lowest CO₂ supply levels for a day
545 reached 39 and 6 kg CO₂ ring⁻¹ day⁻¹, respectively. Our requirements –
546 on average 2.5 kg CO₂ m⁻² day⁻¹ – were very low compared to other FACE
547 systems. For instance, the rice FACE needed on average around 7 kg CO₂
548 m⁻² day⁻¹ (Okada et al. 2001) and the MiniFACE from the BERI project
549 required 6 kg CO₂ m⁻² day⁻¹ to maintain a similar target [CO₂]
550 (Miglietta et al. 2001b). Differences between sites were mainly
551 attributed to wind speed and atmospheric stability (Nagy et al. 1992).
552 For example, the rice FACE site experienced calm conditions during 50%
553 of the experimental season (Okada et al. 2001). Although our
554 experiment required less CO₂ than other similar FACE experiments,
555 other aspects such as the need for a border around the plot for gas
556 mixing and separation of the studied plants from the infrastructure
557 and walkways and the vertical uniformity must be revised in future
558 studies to improve our design and combine the highest performance of
559 FACE technology with the lowest cost possible.

560 For our wetland FACE rings, there were significant correlations
561 between CO₂ requirements and wind speed, air temperature and net
562 radiation, at different temporal scales (Fig. 8). Using 1-min

averages, the rate of ring CO₂ use depended on wind speed through a logarithmic function (CO₂ requirement (kg CO₂ ring⁻¹ h⁻¹) = 0.15*Ln(Wind speed (m s⁻¹)) + 1.67). However, on an hourly scale, CO₂ use was significantly correlated with those variables influencing atmospheric stability, such as air temperature (CO₂ requirement (kg CO₂ ring⁻¹ h⁻¹) = 1.46*Ln(Air temp (°C)) + 3.39) and net radiation (excluding values lower than 1 W m⁻², CO₂ requirement (kg CO₂ 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 CO₂ requirements and wind speed (Okada et al. 2001). This implies a need for improved efficiency of the FACE system in terms of CO₂ usage.

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 732

733 Table 1. Average [CO₂], overall target achievement ratio (TAR) and
 734 fraction of 1-min averages and 24-h averages within ±10% and 20% of
 735 the target value for two wetland FACE rings during the entire
 736 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%
Entireperiod (March-October)								
<i>Ambient</i>	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
Summermonths (July-September)								
<i>Ambient</i>	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

737

738

739 Table 2. Average [CO₂], overall target achievement ratio (TAR) and
 740 fraction of daytime and night time within ±10% and 20% of the target
 741 value using 1-min averages for two wetland FACE rings during the
 742 entire observation period and the summer months.

<u>Daytime</u>					<u>Nighttime</u>				
		<u>Limitfraction</u>					<u>Limitfraction</u>		
	[CO ₂] (μmol mol ⁻¹)	TAR	±10%	±20%		[CO ₂] (μmol mol ⁻¹)	TAR	±10%	±20%
Entireperiod (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
Summermonths (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

743

Table 3. Spearman's rank order correlations (r) between the fractions of time in which $[\text{CO}_2]$ 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	Windspeed	Air temperature
Fraction of time 10% of the target	0.82				
Time (h)	0.54	0.54			
Windspeed (m s^{-1})	0.84	0.76	0.71		
Air temperature ($^{\circ}\text{C}$)	0.84	0.73	0.64	0.92	
Net radiation (W m^{-2})	0.86	0.70	0.43	0.77	0.88

Figure caption

Fig.1. Location of the wetland FACE facility and plan views showing the CO₂ 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) CO₂ 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.

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.

Fig. 4. Dependence of wetland FACE system performance on wind. Upper panel: relationships between [CO₂] and wind speed and direction using 1-hour averages in July 2012. Lower panel: fractions of time in which [CO₂] 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 [CO₂] in F-1 and F-5 rings and wind speed in F-3 ring during the experimental period 2012.

Fig. 6. Daily record of [CO₂] (at 1-min average), wind speed (at 10-min average) and fractions of time in which [CO₂] was within 10% and 20% of the target (at hourly intervals) in ring F-5 during July 6th 2012.

Fig. 7. Spatial distribution of [CO₂] 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,

777 c) air temperature using hourly averages and c) net radiation using
778 hourly averages (excluding values lower than 1 W m^{-2}).