



Effects of Elevated Soil Carbon dioxide (CO₂) Concentrations on Spring Wheat (*Triticum aestivum* L.) and Soil Chemical Properties in Sutton Bonington Campus of the University of Nottingham, UK

¹BIOSE EKENE*, ¹AMAECHI CHIKA FLOYD, ²NNAJI GODWIN UCHE, ³BIOSE OSADEBE; ⁴ERHUNMWUNSE NOSAKHARE OSAZEE

* Author of correspondence: ¹Department of Environmental Management and Toxicology, Faculty of Life Sciences, University of Benin, Benin City, Ugbowo Campus

² Department of Soil Science, University of Abuja, Abuja

³National Centre for Energy and Environment, University of Benin, Benin City

⁴Department of Animal and Environmental Biology, Faculty of Life Sciences, University of Benin, Benin City, Ugbowo Campus
Author of correspondence email: ekene.biose@uniben.edu Tel: 08037162442

ABSTRACT: This study examines the effects of elevated soil carbon dioxide (CO₂) concentrations on spring wheat and soil chemical properties in the Sutton Bonington Campus, of the University of Nottingham, United Kingdom using Artificial Soil Gassing and Response Detection (ASGARD) facility which controls CO₂ injection into the soil. Eight plots (each 2.5 x 2.5m) were laid out within the experimental area and used for the study and were treated with high CO₂ concentrations (area within 75cm from the point of injection), low CO₂ concentration (area farther than 75 cm from the point of CO₂ injection) and no CO₂ concentration (control) at CO₂ injection rate of 1.0l/min from a source point 60cm below the soil for eight (8) weeks. The variability of CO₂ concentrations were determined by 3D and barholing method. The wheat plant showed visible symptoms of wilting, chlorosis and poor development within 15- 21 days of gassing. Gassing at the rate of 1.0l/min resulted in reduced plant height and a 60% decrease in chlorophyll content of wheat plant exposed to high CO₂ concentrations when compared with control plots. The soil pH for the control plots at the depth of 15-30 cm was 6.31 and 6.7 after injection, showing a difference of 0.39. At the depth of 45-60 cm, the pH before injection was 5.89 while post-injection was 6.39, showing a difference of 0.5. The study showed that organic carbon at 45-60cm depth of soil ranged from 2.54% to 2.58% with a mean value of 3.26%, while carbonate content ranged from 0.73 to 0.77%. Furthermore, at 45-60cm depth of soil after injection, the mean value of K across all experimental plots was 64.16 mg/lK, available P content ranged from 15.4 to 16.9 mg/lP, N content ranged from 11.2 to 16.9 mg/lN, Ca ranged from 1000 to 1300 mg/lCa, Mg ranged from 158 to 168 mg/lMg while at 15-30cm depth of soil, Na range from low to moderate (10.16–10.2 mg/l Na). There was no significant difference (P<0.05) or changes in mineralogical content of the soil properties studied. © JASEM

<http://dx.doi.org/10.4314/jasem.v20i2.9>

KEYWORDS: controlled injection; CO₂; soil chemical properties, soil depth

Introduction

Storing carbon dioxide (CO₂) in geologic formations has the potential to be an effective way to reduce atmospheric carbon dioxide levels (IPCC, 2005; Pierce and Sjogersten, 2009; West et al., 2009). Storage sites should be selected to minimise the potential for leakage of stored carbon dioxide to the ocean or atmosphere (West et al., 2009).

The effects of high CO₂ injection in the soil, either through natural or anthropogenic means on plants and microbial communities are poorly understood (Pierce and Sjogersten, 2009). Carbon capture and storage (CCS) is an emerging technology. There is no evidence till date on the long term safety of CO₂

injected into the soil (Celia et al., 2002). Carbon capture and storage involves capturing the CO₂ arising from the burning of fossil fuels, for example during electricity generation, separating it from other waste gases, and transporting it to a site where it will be stored away from the atmosphere for many centuries (Marland et al., 2005). Global carbon-equivalent of CO₂ emissions in 2002 were nearly 7Gt of which UK emissions were approximately 0.15 Gt, of which power generation accounted for about 0.062 Gt (Marland et al., 2005; Defra, 2006).

There are various suggestions for the long-term storage of CO₂, including deposition into the water column in the deep ocean floor and injection into

geologic formations (Marland *et al.* 2005; Defra, 2006). Over pressurisation, poor engineering and pipe line failure could lead to leakage during CO₂ transportation, capture and storage (Pierce and Sjogersten, 2009). The large release of CO₂ due to over pressurisation in geologic media and slow release through faulty systems can occur (Heinrich *et al.*, 2003). However, for effective storage of CO₂ in geologic media, the techniques applied would depend on the reduction of CO₂ leakage from source of release (Pierce and Sjogersten, 2009). The captured CO₂ from a production source can be transported through pipeline, marine tanker or road tankers to the storage site. The risk of severe leaks and the impact from these leaks depends on whether the pipelines are under ground. However, if pipelines are underground, CO₂ can diffuse through the soil into the atmosphere. Slow leaks could increase CO₂ concentrations levels in soil and above plant levels (Pierce and Sjogersten, 2009). The increase in CO₂ levels, also have significant implication for the growth of vegetation and the local environment (Vodnik *et al.*, 2006). Carbon dioxide leakage into the geologic media could be limited but not prevented by safety structures and proper site selection. Slow release of CO₂ and diffusion in the atmosphere could go unnoticed (Pierce and Sjogersten, 2009; Heinrich *et al.*, 2003).

Carbon dioxide has been injected into the soil for various purposes; however, its long term storage is a new concept. The first commercial CCS project was in the year 2000 in Weyburn, Canada (Markels and Barber, 2002). Looking at the long term effect, the storage of CO₂ would have on the environment, it is therefore very necessary to understand the effects of CO₂ leakage on the overlying ecological unit (Heinrich *et al.*, 2003), as toxic concentration of CO₂ in the soil could lead to changes in soil properties and death of vegetation (Pierce and Sjogersten, 2009). Various plants survive differently to anoxic or hypoxic stress and variations in the natural environment (ecosystem) have made it difficult to measure the intensity of exposure (Pierce and Sjogersten, 2009).

Spring wheat (*Triticum aestivum* L.), a member of the *Poaceae* family has a wide range of cultivars. The popularity and large hectares of land used in the cultivation of the crop may be attributed to the survival of a broad range of its species with diverse adaptation and its numerous end-uses (Porter and Gawith, 1999). It is a staple food for about 35 percent of the world's population and; it supplies about 20 percent of the total calorie requirement of the people (Breiman and Graur, 1995; FAO, 2006). There is little research information

on the growth rate and development of agricultural plants in a soil injected with CO₂. Therefore the aim of this study is to determine the effect of CO₂ injection on height and chlorophyll content of spring wheat and on soil reaction and soil properties.

MATERIALS AND METHODS

Study site location: Geology and Description of the Study Area: This study was carried out at the Artificial Soil Gassing and Response Detection (ASGARD) site, Sutton Bonington Campus, University of Nottingham, UK. The University lies between 52.8°N and 1.2°W of Leicestershire, and is approximately 18 km south out of central Nottingham (West, *et al.*, 2009). The site was chosen by the Asgard facilitators on the basis of reasonable uniformity of soil type down to a depth of 1m with good exposure, particularly towards the North, to give room for experimental analysis and for access to facilities (The Asgard Facility Resource Document for UKCCSC, 2007). The study area is located on flat open grassland which was formerly used for sheep grazing. The maximum temperature in January is approximately 6.9°C and the minimum temperature is 1.2°C, and in July, 11.4°C and 21.3°C respectively. The mean annual rainfall of the area is 606mm, which is distributed evenly all through the year (The University of Nottingham Sutton Bonington Metrological Site) (West *et al.*, 2009).

The geology of Asgard site is characterised by up to 1.5m of overlying mudstones of the Mercia group, sand and gravel rich terrace deposits, surrounded by sheets of lithologically variable head (Ford, 2006). A detailed geological description of the site and surrounding area has been described (Ford, 2006). The soil used for the study has a dark brown sandy top soil of approximate 0.3m thickness, a relatively persistent horizon of gravelly head of 0.15m thick, occurring at regular depth of 0.3m to 0.6 m beneath the ground surface was also observed (West *et al.*, 2009)

Field study: Eight plots (each 2.5 x 2.5m) were laid out within the experimental area and used for the study. Carbon dioxide was injected into soil at a depth of 60cm, the CO₂ gas was released from a source which is 60 cm below the centre of each 2.5 x 2.5 m plot. Carbon dioxide was delivered to three plots within the experimental site; the injection rate for all gassed plots was a constant 1.0 l/min for a period of eight weeks. The remaining five plots were controls, without any injection of CO₂ and are distributed among the experimental plots, adjacent to gassed plots (Source: RISCs, 2010). The experimental treatments

were high carbondioxide concentration (area within 75cm from the point of injection), low CO₂ concentration (area farther than 75 cm from the point of CO₂ injection, but within the plots that had CO₂ injected) and control, where no gassing/CO₂ was injected into the soil. A revised 2-D method known as Barholing was used to map CO₂ at 30 cm depth across the plots. This was used to measure the dispersion of CO₂ throughout the plots.

Sample collection, preparation and laboratory analysis: Core samples of soil were collected before and after injection of CO₂ at 75 cm, close to the point of injection (high gas zone) and 225 cm away from the point of injection (low gas zone) in the gassed plot. Core samples were also collected from the control plot. Soils were taken at depths of 15-30 cm and 45-60 cm on the same date after clearing the experimental plots. The core samples collected were air-dried at room temperature 25° C – 27° C for a period of two to three days. The samples were crushed and sieved through a 3mm sieve and packed in a well labeled sample cups for laboratory analysis. They were analysed for the following chemical properties. Soil pH was determined using the pH meter. Total nitrogen and available phosphorus was determined by chemical extraction method, using a spectrophotometer.

Exchangeable bases (Ca, Mg, k and Na) – These were determined by chemical extraction using the Palin test method. Exchangeable bases were extracted using each extraction reagents. Calcium, Mg, K, were read through a spectrophotometer while Na was determined using the flame photometer.

Chlorophyll analysis of wheat plant was determined using the method of Legood (1993).

Determination of plant growth and development: Spring wheat was planted on the 23rd and 24th of March, 2011 at a rate of 350 seeds m⁻² into the eight plots. Wheat seeds germinated on the 5th of April, 2011. Gas was delivered to the plots that received them on the 23rd of May 2011 at a nominal flow rate of 1 Lmin⁻¹ and switched off on the 15th of July, 2011.

The heights of five selected plants were measured using a meter rule in each plot. Data collected were subjected to analysis using Excel to show the temporal changes in the height of wheat plant over control, low gas and high gas zones.

RESULTS AND DISCUSSION

Effects of CO₂ injection on wheat growth and development: Visual observations: In this study, visible change in the growing wheat due to CO₂ injection was observed from 2 weeks of gassing (Plate 1). Generally, there was decrease in growth and discolouration of the leaves of wheat around the point of injection. This visible difference in plants under low gas, high gas and control is in line with results of other researchers (Pysek and Pysek 1989; Smith *et al.*, 2005). Also, Smith *et al.* (2005) observed that the stress effect on pot grown bean and barley crop due to the displacement of O₂ by CO₂, argon gas or water logging was seen to be highest between 14 and 21 days after treatment application. West *et al.*, (2009) noted that monocotyledonous plant, such as grass are more tolerant to high CO₂ concentrations than dicotyledonous species but also stated that other factors, such as nitrogen concentration, plant age and access to photosynthesis can affect plant growth.

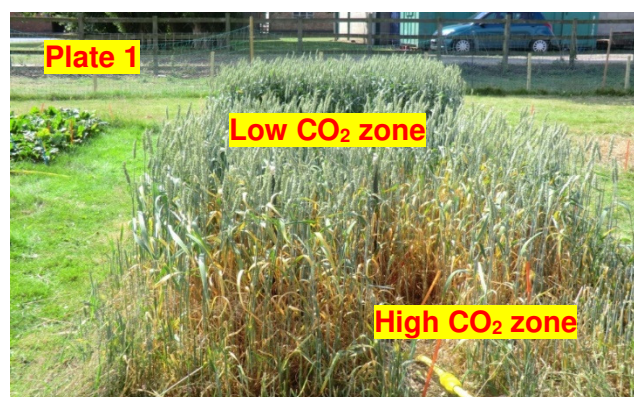


Plate 1 shows a gassed plot with areas of high and low CO₂ zones. Picture taken on 12/07/2011

Plant height: Figure 1 shows the temporal change in the height of wheat. Differences between wheat height grown under control, low and high gas zones was noticed from 15 days of gassing (Figure 1). The height of wheat plant at the centre of the plot was 40 percent higher in the control plot than the gassed plot and 20 percent higher than the edge of the plot. Plants response to high CO₂ concentration was measured at three locations in Slovenia and was found to be generally shorter due to exposure to high CO₂ concentration (Pfanz *et al.*, 2007). This is in line with the findings of other researchers (Smith *et al.*, 2005; Pierce and Sjogersten, 2009; West *et al.*, 2009). Plant under high gas zones were 20 to 40 percent smaller (P<0.05) in height and had fewer leaves than the control plants. There was no significant difference between the control plots and the low gas zones of the

plot but a significant difference ($P < 0.05$) was observed between control plot and the high gas zones of the gassed plots

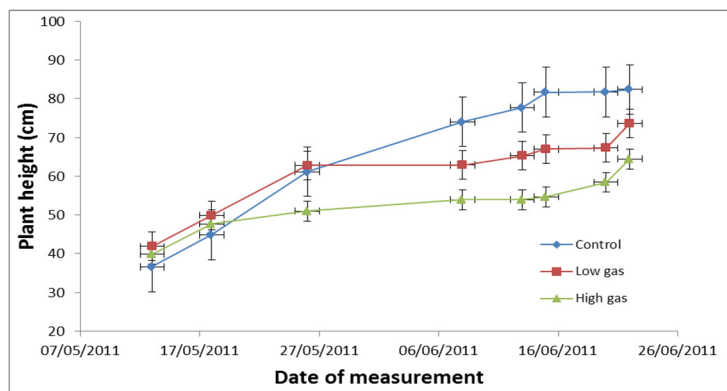


Fig 1: Showing the temporal changes of wheat from germination to full growth and development

The height of wheat plant at the centre of the plot was 40 percent higher in the control plot than the gassed plot. In line with the findings of this study, it was reported that plant height measured at three locations in Slovenia showed that plants on plots under high CO₂ concentration were shorter relative to control plots with low CO₂ concentration (Vodnik *et al.*, 2006; Pierce and Sjogersten, 2009). Schollenberger (1930) carried out a study and noted that areas of leaks from gas pipelines, lead to the death of oat seedlings within 1 to 1.3 m and immature seedlings up to 4 to 5 m, beyond which no damage was visible (Smith *et al.*, 2005). Results from this study also confirmed the findings of other researchers like Hutsch (2001) who noted that different plants have different sensitivity to natural gas zones (Hutsch, 2001). It has been reported that plants grown on naturally high CO₂ levels is affected in a variety of ways (Pierce and Sjogersten, 2009).

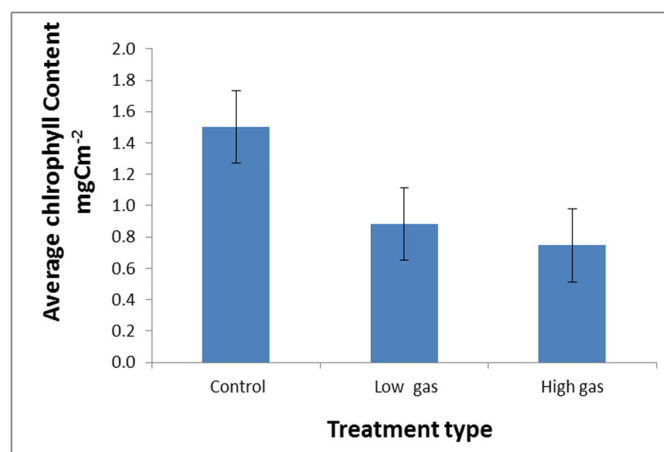
Chlorophyll Analysis: The result of this study shows a 60% decrease in chlorophyll of wheat plant exposed to high CO₂ concentration (high gas zone, at 75 cm from point of injection) and a 40% decrease in chlorophyll of wheat plant at low gas zone (225 cm from point of injection) when compared with control plots (Table 1 and Figure 2).

The changes in the chlorophyll content for wheat plant for control, low and high gas zone of CO₂ experimental plots was expressed on an area basis calculated from.

Chlorophyll (mgcm⁻²) = chlorophyll a + chlorophyll b

Table 1: Effects of treatments on Chlorophyll content (%) of wheat

Treatment	Chlorophyll
Control	1.501
Low gas	0.884
High gas zone	0.746



The percentage difference between the chlorophyll content of wheat leaves of the control, low and high gas area of the plots was calculated using excel. Researchers have also found similar findings. Smith *et*

Fig 2: Average chlorophyll content of wheat plants for control, low and high CO₂ experimental plots

al. (2002) reported that, barley plant which was grown above a leaking natural gas pipeline had a significant decrease of between 15 and 56 % in chlorophyll content. Smith *et al.*, (2005) also noted a decrease of 30% in chlorophyll in monocotyledonous plants exposed to high CO₂ concentrations. Other researchers have reported stress effects in plants due to gas leaks. The symptoms experienced in these plants included yellowing of leaves and shifts in the developmental stage (Schollenberger, 1930; Pysek and Pysek, 1989; Smith *et al.* 2002; Smith *et al.*, 2005). It is important to note that decrease in chlorophyll, especially in a canopy, occurs not only to stress caused by increase CO₂ intake but due to time and spatial distribution of the plant, especially within the canopy. Smith *et al.*, (2005) indicated a drastic decrease in chlorophyll production in oil seed rape that grew in extreme shade when compared to the control growing in open space. However the variations measured in this study are much greater, indicating severe responses to stress caused by CO₂.

Effects of treatments on soil properties: The effects of treatments on soil pH, organic carbon, carbonate, available Phosphorus and Nitrogen contents are given in Table 2.

Soil Ph: Prior to CO₂ injection, the soil pH for the control plots at the depth of 15-30 cm was 6.31 and 6.7 after injection, a difference of 0.39 (Table 2). At the depth of 45-60 cm, the pH before injection was 5.89

while post-injection was 6.39, a difference of 0.5. Hence, there was an increase ($P < 0.05$) in pH.

According to Celia *et al.* (2002), the increase of the concentration of CO₂ influences soil pH which consequently influences the rate of weathering and to some extent, the availability of plant nutrients. However, some researchers indicated that soil injected with CO₂ cause only small changes in the pH of the nutrient solution (Stolwijk and Thimann, 1957; Gahrooe, 1998). Studies have also shown that there is insignificant change in the pH when a high level of CO₂ is introduced to the soil (Ravi *et al.*, 2010). Still other researchers have found a decrease in soil pH after CO₂ has been injected into the soil (Smith *et al.*, 2005).

Organic carbon content: The soil organic carbon content of the studied area ranged from medium to high, values of 2.54% to 2.58% was observed for soil at the depth of 45-60 cm. Soils at 15-30 cm depth ranged from high to very high, values of 3.82% to 4.68% were observed before and after CO₂ injection. The mean value for the experimental plots was 3.26%. This could be attributed to high organic matter returns and other human factors such as reduction in tillage, incorporation of plant roots and residues into the soil (Nnaji *et al.*, 2005). Other cultural practices such as the application of organic manures during agricultural production of crops can also be linked to this. There was no significant difference ($P > 0.05$) in organic matter content of the soils as regards treatment application.

Table 2: Soil pH, average amount of organic carbon, carbonate content and Phosphorus contents for control plot, high and low CO₂ zones at 15-30cm and 45-60cm depth of soil post injection.

Soil properties			
Treatment	15-30cm soil Depth		45-60cm soil depth
		Soil pH	
Control	6.7		6.3
High CO ₂ zone	6.7		6.1
Low CO ₂ zone	6.7		6.9
		Organic carbon (%)	
Control	3.94		2.54
High CO ₂ zone	3.99		2.52
Low CO ₂ zone	3.86		2.59
		Carbonate content (%)	
Control	0.83		0.77
High CO ₂ zone	0.81		0.76
Low CO ₂ zone	0.82		0.73
		Phosphorus (P mg/l)	
Control	44.4		30.6
High CO ₂ zone	47.0		46.3
Low CO ₂ zone	63.3		33.3
		Nitrogen (N mg/l)	
Control	18.2		11.22
High CO ₂ zone	24.4		16.97
Low CO ₂ zone	22.93		15.43

Carbonate content: The carbonate content of soils of the experimental plots was 0.82% at 15-30 cm depth of the soil and ranged from 0.77% to 0.82% at 45 to 60 cm depth of the soil. The high carbonate content of the soils can be attributed to the carbon held in the soil zone, primarily associated with the soil organic content. Carbon plays a significant role in the carbon phase and is therefore very important in obtaining a representation of global climate models (Stevenson *et al.*, 2005). Also, there was no significant difference ($P>0.05$) in carbonate content of soils as regards treatment application. Studies carried out on high concentration of CO₂ soils have reported no difference in carbon content between the treatment and control plots (Pierce and Sjogersten, 2009).

The amount of available P in soil was high across all treatments. Values obtained ranged from 8.57 to 24.4 mg/l. The highest ($P<0.05$) soil P content was obtained in plots of low gas concentration/zone at 15-30 cm soil depth and high gas concentration/zone at 15.30 cm of soil depth.

Table 2 also shows that the amount of N across the experimental plots ranged from 18.2 to 24.4 mg/lN at 15 to 30 cm soil depth and 11.2 to 16.9 mg/l at 45 to 60 cm soil depth. However, the N content of the gassed plot tend to increase at the rate of 4.5 at the various depth of the soil. The lower N content of the control plot may suggest that soil degradation process such as volatilization or leaching was higher in the control plots. Nitrogen is highly mobile in the soil and could thus be lost due to poor soils management and conservation practices adopted by farm manager

Exchangeable bases (K, Ca, Mg and Na): The amount of exchangeable potassium in the control soil was very high ($>80\text{mg/l}$) at all soil depth examined with values greater than that of gassed plots (Table 3). The mean value of exchangeable K across all experimental plots was 64.16 mg/l K which is above 20 mg/l K, regarded as the critical limit of exchangeable K of soil (Onyekwere *et al.*, 2001).

Calcium content was highest in the high CO₂ zone and lowest in soil of low CO₂ zone at 15-30 cm soil depth

(Table 3). The same trend was observed at 45-60 cm soil depth. There was no significant difference between the control and gassed plots at 15 to 30 cm depths of the soil but there was slight reduction of Ca content at 45-60 cm depth of the soil.

Magnesium was 210 mg/l Mg and 182 mg/l Mg in the control plot at 15-30cm and 45-60 cm depths, indicating a slight decrease in Mg with depth. The

amount of Mg in the gassed plot ranged from 158.3 to 178.3 mg/l Mg. Exchangeable Na ranges from low to moderate (9.4–10.2 mg/l Na). There was no significant difference ($P < 0.05$) between the gassed plot and the control plots. However, soils of the studied area was reported to be moderate to high in potassium and sodium contents; this is in line with the findings of (West *et al.*, 2009).

Table 3: Effect of CO₂ injection on soil exchangeable bases content (mg/l)

Soil properties			
Treatment	15-30cm soil Depth		45-60cm soil depth
		Exchangeable Potassium (k)	
Control	83		81
High CO ₂ zone	53.3		60
Low CO ₂ zone	61.7		68.3
		Exchangeable calcium (Ca)	
Control	1450		1300
High CO ₂ zone	1416.7		1083.3
Low CO ₂ zone	1333.3		1000
		Exchangeable Magnesium (Mg)	
Control	210		182
High CO ₂ zone	168.3		158.33
Low CO ₂ zone	178.3		168.33
		Exchangeable sodium (Na)	
Control	10.16		
High CO ₂ zone	10.2		
Low CO ₂ zone	9.37		

Generally, high rainfall leaches away basic soil nutrients down the profile leaving the acidic cation (Al³⁺ and H⁺) at the surface. This may influence salt content and consequently influence electrical conductivity.

Conclusion: From this study it was observed that injection of CO₂ into the soil at a rate of 1.0l/min over 8 weeks had non-significant impact on soil chemical properties studied but has significant effect on wheat growth and development. However, the effects were more in areas with high CO₂ concentration in the soil. Some of the effects included yellowing of the leaves, reduction in plant growth, decrease in chlorophyll content and a significant decrease in above ground vegetation over time. It is recommended that further studies aimed at determining the effects of higher rates of CO₂ injection and duration period on soil and wheat growth should be carried out.

REFERENCES

Breiman, A; Graur, D (1995). Wheat Evolution.
Journal of Plant Science 43: 85-98

Celia, MA; Peters, CA; Bachu, S (2002). *Geological storage of CO₂: leakage pathways and*

environmental risks. American Geophysical Union, Spring Meeting abstract. GC32A-03 in SAO/NASA Astrophysics Data System

Defra, (2006). UK emission of Greenhouse gases – Latest figures. E-digest of Environmental Statistics. London, UK, Department for Environment, Food, Agriculture and Rural Affairs

FAO, (2006). Food outlook. Global market analysis. An Overview. Symposia Announcement: FAO Headquarters, Rome, 14-15 November, 2006. Online: <http://www.fao.org/giews/>

Ford, JR (2006). *The geology of Asgard Site*. Sutton Bonington, Nottingham, British Geological Survey Internal Report IR/06/049R

Gahrooe, FR (1998). Impacts of elevated atmospheric CO₂ on litter quality, litter decomposability, and nitrogen turnover rate of two oak species in a Mediterranean forest ecosystem. *Global Change Biology*, 4:667-677. Doi:10.1046/j.1365-2486.1998.00187.x

¹BIOSE EKENE*, ¹AMAECHI CHIKA FLOYD, ²NNAJI GODWIN UCHE, ³BIOSE OSADEBE;
⁴ERHUNMWUNSE NOSAKHARE OSAZEE

- Heinrich, JJ; Herzog, HJ; Reiner, DM (2003). *Environmental assessment of geologic storage of CO₂*. Laboratory for Energy and the Environment, MIT, presented at the Second National Conference on Carbon Sequestration, Washington D.C. May 5–8
- Hutsch, B (2001). Methane Oxidation in non-flooded Soils as affected by Crop Production – invited paper', *Eur. J. Agron.* 14, 237–260
- Intergovernmental Panel on Climate Change (IPCC), Metz, B; Davidson, O; Coninck, JC; de. Loos, M; Meyer, LA (eds.) (2005). *IPCC Special Report on Carbon Dioxide Capture and Storage*, Cambridge University Press, Cambridge, UK and New York, USA pp. 442
- Legood, R (1993). *Carbon Metabolism*. In Hall, D. O., Scurlock, H. R., Bolhar-Nordenkampf., Legood, R. C. and Long, S. P. (Eds.), *Photosynthesis and Production in a Changing Environment, A Field and Laboratory Manual*. Chapman and Hall, New York, USA, pp. 247–282
- Marland, GT; Boden *et al.*, (2005). *Global, Regional, and National CO₂ Emission*. Trends: A compendium of data on global change. Oak Ridge, Ten., USA, Carbon dioxide Information Analysis Centre, Oak Ridge National Laboratory, US Department of Energy.
- Markels, M; Barber, RT (2002). *Environmental Challenges and Greenhouse Gas Control for Fossil Fuel Utilization in the 21st Century*. Edited by Mercedes Maroto-Valer *et al.*, Kluwer Academic/Plenum Publishers, New York, 2002: "Sequestration of Carbon Dioxide by Ocean Fertilization", pp. 122
- Nnaji, GU; Erutor, PJ; Omokri, OJ (2005). The Chemical Properties of Soils of Orogodo River Basin of Delta State. Proceeding of the 30th Annual Conference of the Soil Society of Nigeria. 5th–9th December, 2005, Markurdi, Nigeria
- Onyekwere, IN; Akpan – Idiko, AU; Amalu, UC; Asawa Lam, DO; Eze, PC (2001). *Constraints and opportunities in agricultural utilization of some wetland soils in Akwa Ibom State*. In management of wetland soils for sustainable agriculture and environment. Proceedings of the 27th Annual Conference of the Soil Science Society of Nigeria. Pp 139–149
- Pfanz, H; Vodnik, D (2004). Plants and geothermal CO₂ exhalations - Survival in and adaptation to high CO₂ environment. *Progress in botany* 65:499–538
- Pierce, S; Sjogersten, S (2009). Effects of below ground CO₂ emissions on plant and microbial communities. *Plant Soil* 325: 197–205,
- Porter, JR; Gawith, M (1999). Temperatures and the growth and development of wheat: A review. *European Journal of Agronomy* 10 (1999) 23–36
- Pysek, P; Pysek, A (1989). Changes in vegetation caused by experimental leakage of natural gas, *Weed Res.* 29
- Ravi, PH; Jeremy, JC; Steven, MD (2010). Effects of CO₂ gas as leaks from geological storage sites on agro-ecosystems. *Energy* 35 4587–4591. www.elsevier.com/locate/energy doi:10.1016/j.energy.2010.01.023
- Research into Impacts and Safety in CO₂ Storage (RISCS) (2010). Establishment of, and Protocols for year 2 Experiment, Project no; 240837, University of Nottingham
- Schollenberger, C (1930). Effect of leaking natural gas upon the soil', *Soil Sci.* 29, 260–266
- Smith, KL; Steven, MD; Colls, JJ (2002). Use of hyperspectral derivative ratios in the red-edge region to identify plant stress responses to gas leaks', *Remote Sens. Environ.* 92, 207–217
- Smith, KL; Colls, JJ; Steven, MD (2005). A facility to investigate effects of elevated soil gas concentration on vegetation. *Water, Air and Soil Pollution* 161: 75–96
- Stevenson, BA; Kelly, EF; McDonald, EV; Busacca, AJ (2005). The stable carbon isotope composition of soil organic carbon and pedogenic carbonates along a bioclimatic gradient in the Palouse region, Washington State, USA. *Geoderma* 124: 37–47

- Stolwijk, J; Thinman, k (1957). On the uptake of carbon dioxide and bicarbonate by roots, and its influence on growth. *Plant Physiology* 32: 513-520
- The University of Nottingham Sutton Bonington Metrological Site, Sutton Bonington Campus, Loughborough, Leicestershire
- Vodnik, D; Kastelec, D; Pfanz, H; Macek, IBT (2006). Small-scale spatial variation in soil CO₂ concentration in a natural carbon dioxide spring and some related plant responses. *Geoderma* 133:309-319
- West, JM; Pearce, JM; Coombs, P; Ford, JR; Scheib, C; Colls, JJ; Smith, KL; Steven, MD (2009). The impact of controlled injection of CO₂ on the soil ecosystem and chemistry of an English lowland pasture. *Energy Procedia* 1 (2009) 1863-1870 www.Elsevier.Com/Locate/Procedia
doi:10.1016/j.egypro.2009.01.243