REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY) 20-05-2014	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 1-Oct-2009 - 30-Nov-2012

4. TITLE AND SUBTITLE
Carbon Sequestration at United States Marine Corps Installations West. Final Report

5a. CONTRACT NUMBER
W911NF-09-1-0560

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHORS
David Mouat, Richard Jasoni, Judith Lancaster, Jessica Larsen, Pablo Marin, Jay Arnone, Erin Adams

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Desert Research Institute - Las Vegas
Board of Regents, Nevada System of Higher Educatior
2215 Raggio Parkway
Reno, NV 89512 -1095

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
57325-EV.1

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

This project was designed to assist Marine Corps Installations West (MCIWest) in developing a strategy to reduce its overall carbon footprint, especially greenhouse gas emissions. The project assessed the carbon footprint at the Marine Corps Air Ground Combat Center (MCAGCC) in part to examine potential sources and sinks for carbon to better understand the potential for natural processes to offset anthropogenic emissions. Previous studies have shown that desert ecosystems might be significant sinks for carbon dioxide (CO2). We undertook a multifaceted approach of MCAGCC to determine landcover (composition and cover). We determined that MCAGCC had

15. SUBJECT TERMS
Greenhouse gases, carbon sequestration, carbon footprint, eddy covariance

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON David Mouat
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU	UU		19b. TELEPHONE NUMBER 775-673-7402

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Carbon Sequestration at United States Marine Corps Installations West. Final Report

ABSTRACT

This project was designed to assist Marine Corps Installations West (MCIWest) in developing a strategy to reduce its overall carbon footprint, especially greenhouse gas emissions. The project assessed the carbon footprint at the Marine Corps Air Ground Combat Center (MCAGCC) in part to examine potential sources and sinks for carbon to better understand the potential for natural processes to offset anthropogenic emissions. Previous studies have shown that desert ecosystems might be significant sinks for carbon dioxide (CO2). We undertook a multifaceted approach of MCAGCC to determine landcover (composition and cover). We determined that MCAGCC had relatively few cover types and that a site could be chosen that was representative of the entire installation. An eddy covariance tower (ET) was located in one relatively homogeneous area in order to assist researchers to determine the net carbon flux of the representative site. Project results indicated that in spite of a low precipitation year, the land surface of the MCAGCC sequestered a significant amount of CO2. Results further indicate that arid shrublands similar to those found at the MCAGCC may play a significant role in modulating anthropogenic greenhouse gas emissions.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received	Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Pablo Marin	0.50	
David Mouat	0.40	
Richard Jasoni	0.30	
Judith Lancaster	0.20	
Jessica Larsen	0.20	
Jay Arnone	0.05	
FTE Equivalent:	**1.65**	
Total Number:	**6**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

Carbon Sequestration at United States Marine Corps Installations West
Phase II

Final Report

David Mouat, Richard Jasoni, Judith Lancaster, Jessica Larsen,
Pablo Marin, Jay Arnone, and Erin Adams

Division of Earth and Ecosystem Sciences, Desert Research Institute, Reno, Nevada

May, 2013

Introduction

A two phase project was designed to assist Marine Corps Installations West (MCI West) entities and organizations in developing a strategy to reduce their overall carbon footprint, especially greenhouse gas emissions. This report covers the second phase of the project, which had three main components:

- an assessment of the carbon footprint at MCI West based on existing information, which was used to develop a science-based profile showing migration pathways;
- an examination of potential natural sources and sinks for carbon, which was conducted to help understand the potential for natural processes to offset anthropogenic emissions.
- and a prioritization of technological solutions for reducing carbons emissions was produced in the context of our understanding of the emissions profiles of the installations.

Because US Marine Corps installations operate in accordance with environmental and other legal requirements, and seek measures that sustain regulatory compliance and operational requirements, MCI West requested a project which would provide Marine Corps Air Ground Combat Center (MCAGCC) Twentynine Palms and other West Coast USMC installations with a strategy for reducing the carbon footprint associated with non-tactical mobile and stationary sources of carbon. The project described in this report contributes to assessing the best strategies for reducing and/or eliminating carbon related emissions at USMC installations in the western region, with a particular focus on MCAGCC and in the context of a significant growth in force within MCI West, and also in consideration of Assembly Bill 32 (AB32) regulations.

Two areas in which the results of this project might be especially important for MCI West are 1), they will assist efforts to comply with California state regulations (AB32) which requires that greenhouse gas (GHG) emissions be lowered to 1990 standards by 2020, and 2), as reducing GHG emissions will be part of a global effort to minimize affects of climate change, MCI West is well positioned to be a proactive player in this activity.

The importance of climate change to land management activities, and agencies' decision making processes is not thoroughly understood, but Federal agencies have been directed to ensure the scientific and professional integrity of their assessment of the ways in which it might affect proposed action (CEQ, 2010). It is recognized that the ability to accurately predict climate change effects, especially in the short term, is limited and the National Environmental Policy Act (NEPA) is recommended as a vulnerability reduction and mitigating strategy technique (CEQ, 2010). Any planning conducted by MCI West must therefore consider the climate change factor.

Regulations

This project was conducted largely in response to regulatory need. As stated in the California State Assembly Bill 32, "Global warming poses a serious threat to the economic well-being, public health, natural resources, and the environment of California. The potential adverse impacts of global warming include the exacerbation of air quality problems, a reduction in the quality and supply of water to the state from the Sierra snowpack, a rise in sea levels resulting in the displacement of thousands of coastal businesses and residences, damage to marine ecosystems and the natural environment, and an increase in the incidences of infectious diseases, asthma, and other human health-related problems." This recognition has led California to take action to regulate greenhouse gas emissions and to reduce its overall carbon footprint.

The State of California is in the process of finalizing regulations on GHG emissions based on the Global Warming Solutions Act of 2006 (California Assembly Bill 32 or AB32). AB32 directs the California Air Resource Board (ARB) to cap all major GHG emissions in the state of California to 1990 levels by 2020. A major emphasis of AB32 is on the electricity and natural gas sectors and carbon reductions in these sectors are critical in reaching the goals of AB32.

On June 26, 2012, the U.S. Court of Appeals D.C. Circuit upheld the Environmental Protection Agency's (EPA) Endangerment Finding and GHG regulations issued under the Clean Air Act (CAA) for passenger vehicles and CAA permitting for stationary sources. This follows the April 2009 ruling by the US EPA which acknowledged that GHGs pose health and safety risks. The ruling comes after the 2007 Supreme Court decision required the EPA to review the justification in regulating GHGs under the Clean Air Act. The evolution of AB32 and the decision by the EPA that GHGs are a health and safety risk, demonstrate that the national trend will be to regulate the production of GHGs. In addition to regulatory standards, Cap and Trade methods or carbon tax may be employed as additional methods to control GHG emissions.

Relevance

There are several factors which indicate that the MCAGCC is an important study site for military compliance to reduce GHG emissions and reduce its carbon footprint. The southwestern US is a mosaic of land uses, land ownership, and varying ecoregions. The Department of Defense manages a considerable inventory of installations and facilities in this region - approximately 40,000 km^2 in Southern Nevada, Southeast California, and Western Arizona - which were once relatively remote and had a very low population density. However, most of them today are near or even adjacent to urban development due to unprecedented growth in the Southwest, which is among the highest in the country. This juxtaposition of military lands with areas of rapid urban growth and a tendency toward a "green" demographic provides a suitable context for demonstration of military preparedness not only in terms of defense, but also in the wider global scenario of the effects of climate change.

Arid regions, such as the context area of MCAGCC, are increasingly being looked at as potential areas for assessing CO_2 flux. The military may become a major player in managing lands for its training and testing activities as well as for sequestering carbon.

Sources and Sinks

CO_2 cycling between the terrestrial surface and the atmosphere

Carbon dioxide (CO_2) cycles between the atmosphere and terrestrial ecosystems/sources and there are several sources and sinks for CO_2 on the Earth's surface (Figure 1). One of the major sources of CO_2 into the atmosphere from Earth's surface is from the burning of fossil fuels. The burning of fossil fuels accounts for the majority of CO_2 that is emitted into the atmosphere. Other sources of emission include animal and plant respiration (above and belowground respiration), soil heterotrophic respiration, and dead and decaying animal and plant tissues. The major sinks for atmospheric CO_2 include plants, soils (if managed properly), soil biological crusts (photosynthesizing organisms on the soil surface that can take up or release CO_2), and oceans. Many factors affect the strength of these various sources and sinks for CO_2. Plant source or sink strength is usually determined by the type of plant, the leaf area index of the plant, the canopy cover per unit of land area, soil nutrient availability, and environmental factors such as temperature and precipitation which can change dramatically within and between years (intra and inter annual variability).

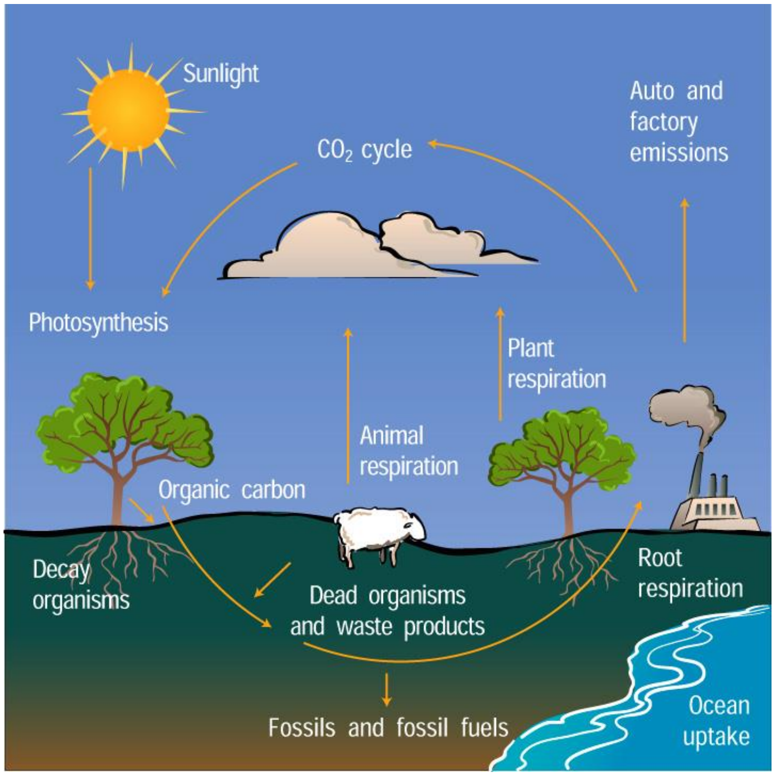

Figure 1. Carbon dioxide (CO_2) cycling between the atmosphere and terrestrial ecosystems and other sources.

Carbon sequestration potential of arid shrublands

Deserts (arid and semiarid) cover >30% of Earth's land surface and are also home to >30% of its population. Arid desert shrublands similar to the Mojave occupy approximately 20% of the Earth's land surface. The extent to which these deserts currently modulate global atmospheric CO_2 levels is poorly understood. This is because of the worldwide paucity of empirical measurements of net ecosystem CO_2 exchange (NEE; the instantaneous net ecosystem CO_2 flux) in desert and semiarid biomes (Falge et al., 2002a, b; Law et al., 2002). This, in turn, is perhaps due to the perception that sparse vegetation cover and seemingly bare soil surfaces translate into a low net annual positive ecosystem CO_2 balance (net ecosystem productivity, NEP; the annual sum of NEE) or even to a neutral or negative balance. Certainly biomass carbon stocks of arid shrublands pale in comparison with forests hectare for hectare (Grace, 2004) and their net primary production (NPP) is considered among the lowest of any ecosystem type (Larcher, 2001). However, existing NEE and NEP data from sparsely covered (5–20% plant cover) arid shrublands indicate that deserts may rival or even exceed net CO_2 uptake by forests and grasslands, at least in some years (e.g., years with high precipitation) (Table 1). Wohlfahrt et al. (2008) measured carbon fluxes from a Mojave Desert shrubland using the eddy covariance method and measured an annual NEP of -102 ± 67 g C m^{-2} (2005), -110 ± 70 g C m^{-2} (2006), and -81 ± 52 g C m^{-2} (2007; unpublished eddy covariance data from this Mojave Desert shrubland) (note: negative NEP values are net uptake of CO_2 by the ecosystem), indicating that the Mojave Desert ecosystem studied was a significant net sink for CO_2 during the 2-year study (2005 – 2006), corroborating the annual net gains of -127 ± 17 g C m^{-2} measured in 2004 by Jasoni et al. in the nearby ambient CO_2 FACE plots using large static ecosystem chambers (Jasoni et al. 2005). These sink strength estimates are in line with the few other studies available in the literature: -212 g C m^{-2} (March–December only) reported by Scott et al. (2006) for a semiarid riparian shrubland in Arizona, -39 to -52 g C m^{-2} found by Hastings et al. (2005) for a desert shrub community in Baja California/Mexico, -96 to -155 g C m^{-2} determined under normal weather conditions by Luo et al. (2007) for a mature semiarid chaparral ecosystem in California (under severe drought conditions this ecosystem was found to be a large source of CO_2; 207 g C m^{-2}, and -7 to -59 g C m^{-2} for a Great Basin arid shrubland ranging in canopy cover from 35 to 20% (unpublished data). Emmerich (2003), though, reported a net annual loss of 144 g C m^{-2} in a semiarid bush site in Arizona, however, this loss appears to stem from the large pool of soil inorganic carbon. Thus, these high NEPs and the large global extent of the arid and semiarid biome (>30% of Earth's land surface; Lal, 2004) strongly suggest that deserts are playing a much larger role than previously expected in modulating atmospheric CO_2 levels. Expansion of arid shrubland vegetation cover, similar to that observed in the Mojave Desert of the southwestern United States over the past three decades (Webb et al., 2003), or potential increases in the activity or land-area-based mass of cryptobiotic crust communities that cover large areas of desert soil (Evans & Johansen, 1999; Belnap et al., 2004) may be contributing to the large positive NEPs that have been measured. Although there is evidence indicating that deserts of the world sequester carbon, and in some cases large amounts of carbon, it has been suggested that intra- and inter annual variability as well as properly accounting for measurement errors play a large role in determining the true role of desert ecosystem carbon sequestration (Schlesinger et al. 2009).

Table 1. NEP values measured using static chamber and eddy covariance (EC) methods.

Desert	Location	Year	NEP (g C m-2 yr-1)	Notes	Reference
Mojave	S. Nevada	2004	-127	Chamber measurement	Jasoni et al. 2005
		2005	-102	Eddy covariance	Wohlfahrt el al. 2008
		2006	-110	Eddy covariance	
		2007	-81	Eddy covariance	Unpublished
G.Basin	E. Nevada	2006	-18	Eddy covariance	
			-59	Eddy covariance	
			-56	Eddy covariance	
		2007	-7	Eddy covariance	
			-53	Eddy covariance	
			-59	Eddy covariance	
Sonoran	Baja Calif.	2002	-39	Eddy covariance	Hastings et al. 2005
		2003	-52	Eddy covariance	
	S. California	1998	-96	Eddy covariance	Luo et al. 2007
		2000	-100	Eddy covariance	
		2001	-155	Eddy covariance	

Sequestration at MCAGCC

There are capture and storage opportunities at the Marine Corps Air Ground Combat Center (MCAGCC) at Twentynine Palms. California currently operates two Combined Heat and Power (CHP) systems. While these systems do produce GHG emissions, the total output of 16.4 MW is much less than when compared to a large scale power plant. For a scale comparison, when the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL) published its *Coal-Fired Power Plants in the United States: Examination of the Costs of Retrofitting with CO_2 Capture Technology, Revision 3*report, it excluded power plants from the analysis that had a capacity less than 100 MW (2011). In addition, all of the references for this section were compiled from papers, journals, and other sources related to larger-scale power producing operations and carbon capture and storage (CCS) projects because no notable information on CCS projects at a small-scale is available. See Appendix A for more details on the potential cost of doing CCS on the MCAGCC cogen plant.

Carbon sequestration and storage operations require substantial capital to operate and maintain even when suitable environmental conditions are present. The feasibility of carbon capture and storage (CCS) is divided into three components or steps: 1) CO_2 capture and compression, 2) transportation of $CO_2$with pipeline being the most used, and 3) underground storage (ICF Inter. 2009). In general, components 1 and 3 will have higher costs and the most challenges when compared to component 2.[1]Component 2, the transportation of CO_2can be done by vehicle transport or by pipeline. The pipeline industry and technology for transporting gasses and liquids is well established, therefore transporting CO_2via pipeline is the most used for ease of implementation and lower costs. Components 1 and 3 costs and methods will be dependent on the type of fossil fuel(s) and the system used to produce the energy and/or heat, CO_2 capture system, location of storage site, and whether or not it will be used for enhanced oil recovery (EOR).[2]A 2009 paper for the Interstate Natural Gas Association of America (INGAA) lists general CCS component costs for capture as ranging from zero to over $50/tonne (costs are measured by metric tonne), compression would add $9 to $15/tonne, transportation via pipe and pumping ~$4.60/tonne per 150 miles, and -$40 (EOR use) to $20+/tonne for injection depending on use or site (ICF Inter). In addition to the operating costs are upfront expenses that increase the cost of a new CCS power plant by 15%-30%, and even more to retrofit an existing plant with CCS (MIT 2007, Rubin et al. 2007).

Site selection and development for CCS facilities can range from 3-10 years and require extensive studies (Cooper et al. 2009) including detailed geologic studies, without which, a storage site cannot be considered adequate. But assumptions with current available data can be used to compile potential options for onsite CCS. If MCAGCC were to develop onsite CCS with injection into a saline aquifer, the Dale Valley Groundwater Basin would be most suitable when compared to other groundwater basins in the area. Water quality of the Dale Valley Basin aquifer is unsuitable for domestic and agricultural use. The basin itself may have a large storage capacity and is isolated from other potable groundwater basins (CA Dept. of Water 2003). These general attributes are considered by experts to be the most important for storage of CO_2 in saline aquifers. The groundwater basin information and Geographic Information System (GIS) data was acquired from the California Department of Water Resources. Like other agencies that share GIS data with the public, the California Department of Water Resources cautions users about the potential for errors and quality of the data. Without a detailed hydrologic study of the area, it is unclear if the Dale Valley Basin is connected to the Pinto Valley Groundwater Basin or is an error in the data. The Pinto Valley Groundwater Basin is shown abutted to the southeast boundary edge of the Dale Valley Basin. The shared boundary is displayed in a GIS shapefile, but is not referenced in the logs, reports, or other maps.

Future opportunities to connect to CO_2 transmission pipelines should also be considered. The U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL) is

---

[1] See these reports: "A Technical Basis for Carbon Dioxide Storage," by Members of the CO_2Capture Project and edited by Cal Cooper; "Developing a Pipeline Infrastructure for CO_2Capture and Storage: Issues and Challenges," by ICF International

[2] Enhanced oil recovery (EOR) is the last phase of oil recovery after primary and secondary recovery. CO2 used for EOR is injected into the reservoir and as it expands, it pushes oil to a production well while dissolving in the oil and lowering its viscosity and improving the flow rate. EOR can account for 30 to 60 percent, or more of the reservoir’s original oil in place (DOE’s Fossil Energy Office of Communications 2011).

developing a technology portfolio that will include cost-effective commercial-scale CO_2 capture, storage, and mitigation technologies that will be available for commercial deployment beginning in 2020 (2010). As a result, regional and commercial CCS projects are expected to materialize (NETL 2010) and will require extensive CO_2 transmission pipelines. ICF International's 2009 report to Interstate Natural Gas Association of America developed four future scenarios for CO_2 transmission pipelines in the United States for 2030: The High CCS with (projected) enhanced oil recovery (EOR) scenario would require 20,610 miles of pipeline; the High CCS with Greater EOR scenario would require 36,050 miles of pipeline; the Low CCS with (projected) EOR scenario would need 5,900 miles of pipeline; and the Low CCS with the Greater EOR scenario would require 7,900 miles pipeline. ICF International's projections remain dependent on countless factors, but even in the conservative case, a significant amount of transmission pipeline will be created. Therefore, the potential for MCAGCC to connect to a CO_2transmission pipeline and be managed by another party may become an option in the near future.

Sequestration of carbon in the terrestrial biosphere has emerged as the principal means by which the US will meet its near-term international and economic requirements for reducing net carbon emissions (Unkefer et al. 2001, DOE 1999). The research team has found that the terrestrial biosphere at MCAGCC can sequester a significant amount of CO_2.Currently, MCAGCC’s on site vegetation is estimated to sequester (-102,650 ± 60,299 metric tons of C/MCAGCC land area/year) with a ~10% average vegetation cover(discussed later in this report). Plant community structure in arid environments is strongly shaped by disturbance regimes and prolonged drought (Herberl and Gibbens 1996). And studies conducted in the Chihuahuan Desert on vegetation dynamics show that improved management practices or favorable moisture periods in canopy cover similar to MCAGCC's can increase canopy cover (Havstad et al. 1999). Agriculture, urban development, military maneuvers, pipeline, road and power line construction, and recreation vehicles all destroy vegetation cover and expose the soil to wind erosion (Herberl and Gibbens 1996, Watts 1998). MCAGCC cannot cease military maneuvers and training, but incorporating varying degrees of land management can preserve and improve vegetation cover. Land management techniques as simple as conducting operations in areas already disturbed with natural windbreaks such as hills, and mountains would limit degradation of vegetation (Okin et al. 2001,). Land managers can administer more complex schemes and use integrated framework management systems and plan for climate change and the affects to local vegetation.[3]

Existing vegetation should be protected when possible, but cultivating additional vegetation for carbon sequestration to offset anthropogenic carbon emissions might be practicable to

---

[3] See these articles: *An Integrated Framework for Science-based Arid Land Management*. J.E. Herrick, B.T. Bestelmeyer, S. Archer, A.J. Tugel, J.R. Brown. Journal of Arid Environments 65 (2006) 319-335; *Degradation of Sandy Arid Shrubland Environments: Observations, Process Modelling, and Management Implications*. Gregory S. Okin, Bruce Murray & William Schlesinger. Journal of Arid Environments 47 (2001) 123-144; A multi-scale classification of vegetation dynamics in arid lands: What is the right scale for models, monitoring, and restoration?. B.T. Bestelmeyer, D.A. Trujillo, A.J. Tugel, K.M. Havstad. Journal of Arid Environments 65 (2006) 296-318.

implement, cost less, and be less environmentally intrusive than a ground water basin CCS project. MCAGCC receives little precipitation and uses all of the water that is extracted from groundwater basins. MCAGCC has stated there is no available source of water that can be used for vegetation irrigation. The research team understands that it is not feasible to irrigate vegetation for carbon sequestration because of limited water availability. Nevertheless, we think it is important to discuss the possibilities of using halophytes for CO_2 sequestration. Of course, a large-scale halophyte farming operation would require considerable study to determine if such a project could remain operational and the CO_2 sequestration would warrant the cost and resources.

The chemical composition of water, climate, soil characteristics, drainage conditions and the irrigation method, and water management would need to be addressed to determine if a halophyte farm is sustainable in a given location. If the needed criteria and resources for a halophyte farm could be met at MCAGCC, brackish water and wastewater might be used. In a project in Spain where biosolids were added to degraded soils in semiarid environments, the biomass production increased more than 200%-900% (Navas et al. 1999, Albaladejo and Stocking, 1994). While applying bio solids to arid and semiarid soils is not always agreed upon, the potential to degrade poor soils further is low (Lado and Ben-Hur 2009, Navas et al. 1999, Beltrán 1999) and is a less volatile process to manage. Researchers studied growth, water use, and salt uptake of four halophytic species: *Atriplex nummularia* Lindl., a C_4 perennial shrub; *Distichlis palmeri* Fassett, a C_4 perennial saltgrass; *Batis maritima* L., a C_3 perennial succulent; and *Suaeda esteroa* Ferron and Whitmore, a C_4 annual succulent. Researchers found that the list of halophytes can be grown productively with water classified as brackish (5-20 g l^{-1}) and can grow when applied with salinity solution as high as 40 g l^{-1}(Miyamoto et al. 1996).

This project would also require special attention on various components to maintain farming operations. The biggest need would be for less brackish or even better quality water. Depending on whether natural drainage or subsurface drainage is used, leaching of salts and dissolved minerals would be required (Beltrán 1999) to maintain the optimal water mixture (i.e., using the least amount of higher-quality water to reduce or remove salt). This high salinity drainage water, in most cases, is in excess of the seawater salinity (35 g l^{-1}) (Miyamoto et al. 1996) and can be disposed of in evaporation lakes or even injected into confined aquifers (Beltrán 1999). The concept of a halophyte project is not insensitive to the required prudent water management at MCAGCC and the surrounding communities. Instead, the scope of the project is to look at all possibilities and resources for consideration.

Eddy Covariance Study - Materials and Methods

Study site

The study site is located on the grounds of the MCAGCC (34°18’37” N 116° 15’8” W) near Twentynine Palms, California. The plant communities at the MCAGCC are dominated by the evergreen shrub creosote bush (*Larrea tridentata*). The density of annual plants that occur at this site depends on the amount and seasonality of rainfall (Jordan *et* al., 1999; Jasoni *et al.*, 2005). Percent perennial plant cover at the MCAGCC is approximately 10% (this was determined through a multi-faceted approach that will be described subsequently). The site receives an average of 108 mm of precipitation per year (http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?catwen+sca; July 1, 1948 – December 31, 2005) and has an average annual temperature of 20 ºC (http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?catwen+sca; July 1, 1948 – December 31, 2005).

Vegetation Cover Mapping

The MCAGCC landscape is a patchwork of varying soils and landforms, each with its associated vegetation. Plants occupy spatial niches which are defined by soil, climate and topography and comprise a number of co-existing species. Because carbon flux is calculated from surface vegetation, it was necessary to map the vegetation of the installation. An initial reconnaissance of MCAGCC indicated that there were three basic vegetation types (and a barren class) with some variation. These types are creosotebush dominated types and bursage (*Ambrosia dumosa*) dominated types that occur over most of the Base and riparian types dominated by mesquite (*Prosopis juliflora*) and smoketree (*Psorothamnus spinosus*).

The eddy covariance tower (ET) was located in an area which is representative of the entire MCAGCC in terms of vegetation composition and cover, soils and landforms. Both plot and regional data were gathered to discern landform, vegetation and soil variables and quantify vegetation cover.

Six components provided input at plot and local scales:

- Remote sensing and GIS
- Landform assessment
- High resolution imagery
- Helicopter survey data
- Information from a 1998 soil survey report
- Ground-based surveys

Determining land cover was accomplished using a multifaceted approach that integrated satellite imagery with high resolution sensor data and digital camera images. No single sensor provides all the information needed for vegetation mapping (Xie et al., 2008) and typically images from several sensors are combined and correlated, as was done for this project. A Geographic Information System (GIS) was used to georeference and integrate data, delineate the tower site survey boundary and plot data; providing maps, statistics and, most importantly, the ability to scale up and down as needed.

In the GIS, a geomorphic raster dataset for the region was transformed into a vector file to display soil composition and delineate soil groups. A landform map was available for the base as was a soils map specifically developed for the base, and both these were used to further define the geomorphic soil data and identify and categorize vegetation by soil composition, which was then entered into a GIS database.

Because plant species are constrained by soils, climate and topography, landform is a robust indicator of plant composition and cover (e.g., Mouat, 1974) and landform is also a dominant feature, both on the ground and when viewing imagery, for arid and semi arid areas where vegetation is sparse. Combining the results of this multi scale and multi resolution approach with a soils and topographic data provided a landform map (Figure 2) which was the primary georeferenced source for this component of the project.

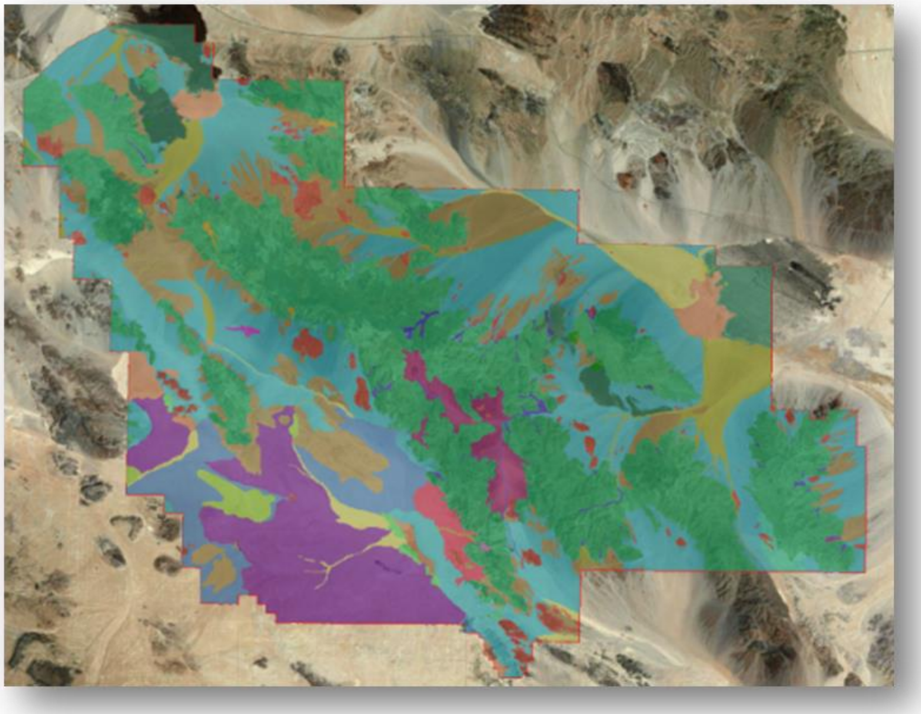

Figure 2. Landform types of MCAGCC. Mountains shown in green, consolidated alluvium in blue and brown, unconsolidated alluvium in purple, bare ground in dark green and riparian and washes in light beige.

Initially, common automatic computer classification methods including supervised classification and unsupervised classification methods were conducted on image data, but these methods proved to be unsuccessful because of the scale of the data. As a result, man-computer interactive interpretation was used, which resulted in higher accuracy than automatic computer interpretation. The man-computer interactive classification approach also relied on visual interpretation of ArcMap’s Bing base map and other thematic base maps.

Researchers then visited all soil groups depicted in the GIS data to conduct a soil analysis and vegetation assessment. The combination of helicopter reconnaissance plus field reconnaissance proved to be useful for determining cover. The field visit data was used to adjust the GIS data used to calculate vegetation composition and cover. Lastly, Mouat and Marin flew a helicopter reconnaissance of much of the base on September 21, 2011, including all landform types. They both took 100s of high-resolution georeferenced digital photographs (taken at an angle perpendicular to the surface of the earth). The georeferenced photographs were then rectified in GIS and used to make the final adjustments of the remote sensing data. The helicopter reconnaissance proved to be invaluable for assessing cover accurately. Ultimately, the research team decided on five groups to represent the land cover of MCAGCC as shown in Table 2.

Table 2. Quantification of landform type in the eddy covariance tower area.

Landform Group	**Area (km_2)**	**Ave Veg Cover (%)**
Bare	133	0.53
Mountainous	840	8.70
Consolidated Alluvial	1147	10.12
Unconsolidated Alluvial	141	7.68
Riparian	144	11.82

Eddy covariance and meteorological instrumentation

Eddy covariance is used to determine the exchange rate between the atmosphere and plants by measuring the covariance between fluctuations vertical wind velocity and CO2 mixing ratio. In June 2011, a 5-m tall EC and a 3-m tall meteorological tower were installed at the site (Figure 3). The instruments installed on the 5-m EC tower consisted of a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, Utah, USA) to measure the three wind components, and an open-path infrared gas analyzer (IRGA) to measure CO_2 molar density (LI-7500, LI-COR Inc., Lincoln, Nebraska, USA) and were positioned downwind of the predominant wind direction to capture CO_2 fluxes of the vegetation cover. All sensors on the EC tower were mounted 4.25 m above mean vegetation height on the south (predominant wind direction) side of the tower. The sensor height above mean vegetation height was selected to increase the number of points within the footprint and to avoid interference from sources outside of this area. The ensuing larger high-frequency flux contributions and unavoidable low-pass filtering caused by the sensor height was accounted for during post-processing using the method described by Massman (2000). The instruments installed on the 3 m meteorological tower consisted of a shielded air temperature and humidity sensor (HMP-45C, Viasala, Finland; mounted 2.0 meters above ground surface), wind vane anemometer (RM Young Wind Sentry, RM Young Company, Traverse City, MI, USA; mounted 2.5 meters above ground surface), net radiometer (NR-Lite, Campbell Scientific, Logan, UT, USA; mounted 1.8 meters above ground surface), photosynthetically active radiation sensor (Q-190-SB, Campbell Scientific; PAR, 400-700 nm;

mounted 2.5 meters above ground surface), tipping bucket rain gauge (TE525, Texas Electronics, Dallas, TX, USA; mounted 2.5 meters above ground surface). Soils instrumentation included : soil heat flux plates (Hukse flux HFP01SC, Campbell Scientific, inserted at 8-cm soil depth), soil temperature thermocouple probes (TCAV averaging soil thermocouple probes, Campbell Scientific; installed at 2 and 6-cm soil depth adjacent to the soil heat flux plates), and a soil moisture probe (CS-616, Campbell Scientific; installed at a depth of 8 cm). Data from the EC instrumentation were recorded with a data logger (CR5000, Campbell Scientific) at a frequency of 10 Hz (10 times per second) while data from the other instrumentation were recorded as 30-min averages. Both the 10 Hz and 30-min averages were stored on a compact flash card. Data from the compact flash card were downloaded monthly when instruments were also checked and maintained. The data were also transmitted to the Desert Research Institute (DRI) via a CDMA modem every hour, and stored on a data server located at DRI in Reno. Eddy covariance was calculated using the methods described in Appendix B.

Figure 3. Photograph of the eddy covariance (EC) instrumentation at the Marine Corps Air Ground Combat Center (MCAGCC) near Twentynine Palms, California. The instrumentation was installed on June 15 2011.The rightmost tripod tower in the photograph is the 5-m tripod tower and contains the EC instrumentation. The leftmost tower in the photograph is the 3-m tripod tower and contains the meteorological instrumentation.

Analysis

With any study involving instrumentation there are inevitably some gaps in data. The method used to fill these gaps, in order to obtain continuous values, is described in Appendix C.

Results

Footprint measurement analysis

The measurement footprint that was calculated for the one year study had an area of 30,426 ha^2 (Figure 4). Within the footprint, the average plant canopy cover was 10 percent. The footprint encompassed an area that contained representative vegetation and canopy cover typically found in this area, but excluded houses to the south and west, and "main side" (the main population center of the MCAGCC) to the east of the EC instrumentation. The exclusion of these areas prevented contamination from sources other than the desired land area. Calculations for the procedure used are shown in Appendix D.

Systematic uncertainty

The largest contributor to the overall systematic uncertainty was the uncertainty in the quantification of the sensible heat fluxes (Table 3). Uncertainty in the quantification of sensible heat fluxes accounted for 99 percent of the overall systematic uncertainty. Air temperature, water vapor density, static air pressure, and quantification of latent energy accounted for the remaining one percent of the overall systematic uncertainty.

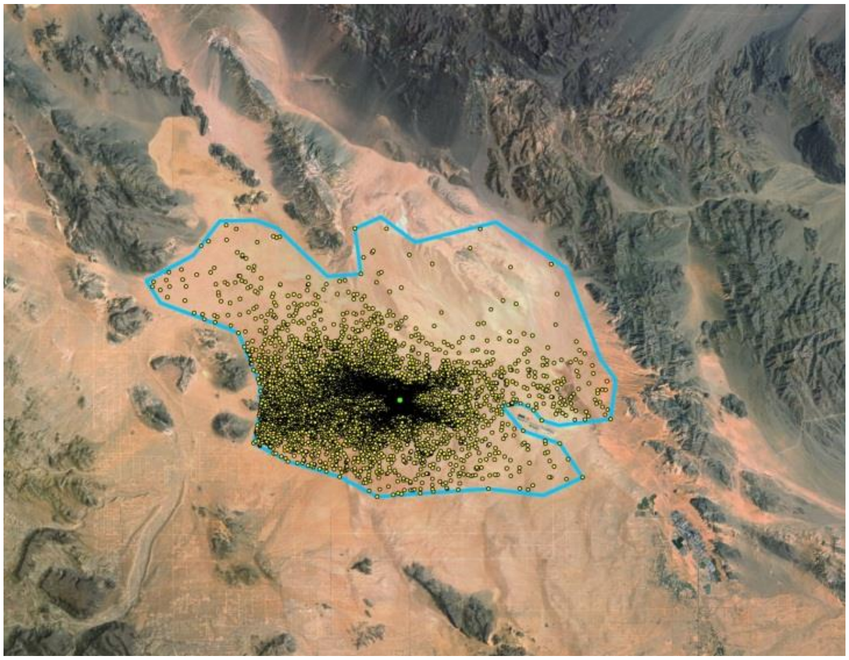

Figure 4. Data collection for the measurement footprint at the Marine Corps Air Ground Combat Center (MCAGC, light blue line). The green dot indicates the location of the EC tower. Yellow points represent individual 30-min flux values measured by the EC instrumentation between June 15, 2011 and June 15, 2012.

Table 3. Total systematic uncertainty of annual net ecosystem CO_2 exchange (NEE) (g C m^{-2} $year^{-1}$) calculated as the square root of the sum of the squared individual sources of uncertainty using density corrected data (Webb et. al.,, 1980) for the Marine Corps Air Ground Combat

Center (MCAGCC) for the period of June 15, 2011 to June 15, 2012.T_{air} – air temperature; ρv – H_2O density; P – air pressure; F_H – sensible heat before accounting for density effect and storage flux; F_{H2O} – latent energy before accounting for density effects and storage flux.

Source of uncertainty	(g C m^{-2} $year^{-1}$)
T_{air} (2%)	0.0
ρ_v (10%)	0.2
P (10%)	0.7
F_H (5%)	25.0
F_{H2O} (5%)	0.1
Total systematic uncertainty (g C m^{-2} $year^{-1}$)	± 26

Meteorological conditions during the study period

Air temperature ranged between -6 and 41 °C (Figure 5), with an annual average of 19 °C which is close to the annual average for Twentynine Palms (1948 – 2005) of 20 °C. Soil temperature ranged from -1 to 50 °C, with highest soil temperatures occurring during the summer and the coolest temperatures during the winter. Annual precipitation during the study period amounted to 11 mm, almost an order of magnitude lower than the 1948 – 2005 annual average of 108 mm. Daily average soil water content ranged from 2 to 4 vol. %. Photosynthetically active radiation showed typical diurnal and seasonal patterns with the lowest PAR values during the winter and highest PAR values during the summer. Periodic dips in PAR throughout the study year reflected cloudy conditions.

Missing data

During the one year study, 27 percent of the 30-min NEE values were gap filled using the mean diurnal variation method. Gaps in the data resulted from inferior quality data being removed because of the quality control filtering methods that were used in this study (see Materials and Methods section above) and because of the exclusion of points when the footprint of the footprint was created. Data gaps of this nature are unavoidable, and very common in EC data sets, but still allow for accurate estimates of annual carbon sequestration (Baldocchi 2003) when accurate gap filling techniques are used. The mean diurnal variation method was extensively tested along with 15 other gap filling methods, and was shown to be accurate (Moffat *et al* 2007).

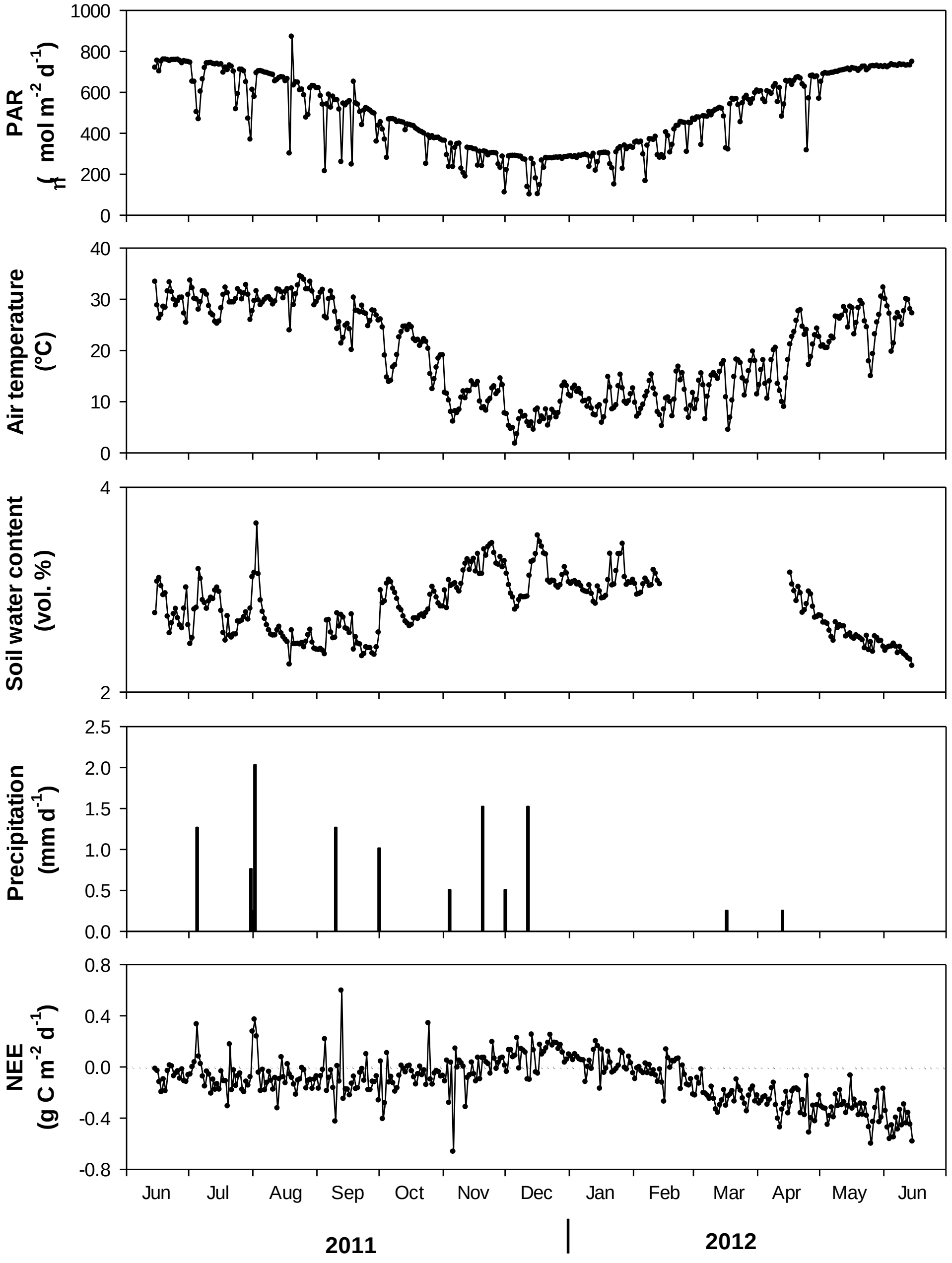

Figure 5. Daily photon flux density of PAR (a), mean daily air temperature (b), mean daily soil water content (SWC) (c), daily precipitation (d), and net ecosystem CO_2 exchange (NEE) (c) measured at the MCAGCC between June 15, 2011 ND June 15, 2012. Data are missing from soil water content between 2/15/2012 to 4/17/2012 because of soil moisture sensor malfunction.

Net ecosystem CO_2 exchange and annual C sequestration

Daily NEE during the one-year study varied from day-to-day and seasonally, but with CO_2 uptake occurring during most of the year (Figure 6 i.e., mostly negative NEE values). There was a brief period of time between late November 2011 and mid-January 2012 when release of CO_2 to the atmosphere dominated,averaging+0.1 g C m^{-2} d^{-1}. Highest uptake rates were observed between March and June 2012 (-0.3 g C m^{-2} d^{-1}) and lowest uptake rates between June and November 2011 (-0.1 g C m^{-2} d^{-1}). Daily NEE for the one-year study ranged from a release of 0.6g C m^{-2} d^{-1} to an uptake of -0.7g C m^{-2} $d^{-1}$with a mean of -0.1g C $m^{-2}d^{-1}$. Spikes in NEE occurred during or immediately after rainfall. Annual carbon sequestration within the footprint (with 10 percent canopy cover) was -43±26 g C m^{-2} $year^{-1}$ (102,650 ± 60,299 metric tons of C $year^{-1}$ when extrapolated to the entire MCAGCC land area [250,000 ha]). As discussed in the section describing canopy cover estimation. The average canopy cover throughout MCAGCC was very nearly exactly the same as the canopy cover for the footprint. In addition, the species composition was also comparable.

Simple linear regression analysis showed that changes in NEE were significantly ($P<0.0001$) related to daily average air and soil temperatures, average daytime PAR Flux Density (PFD), average daytime net radiation, and daily average soil water content.Net ecosystem exchange was not significantly related to precipitation (Figure 7). However, all statistically significant regressions had low r^2 values ranging from 0.07 to 0.28, indicating a low power for any of these environmental variables on their own to predict variations in NEE. However, when all of these variables were included in a multiple linear regression, the r^2 value increased to 0.5.

Discussion

At an annual rate of -43±26 g C m^{-2} $year^{-1}$ the MCAGCC was a net sink for atmospheric CO_2 during the one year study period (Figure 8). A significant portion of this uptake occurred in the summer and fall of 2011 that corresponded with the timing of growth of new *Larrea* shoots and foliage and the emergence and growth of herbaceous annuals and perennials. Most of the annual CO_2 uptake, however, occurred from February to June of 2012 (Figure 6) in spite of the lack of rain during this period. Non-extreme air temperatures prevalent during this period likely kept atmospheric vapor pressure deficits below levels that inhibit leaf stomatal conductance (e.g., Oren 1993; Bunce et al. 1984; Körner 1994) and photosynthesis (Arnone et al. 2008). It appears that strong plant growth during the spring and early summer of 2012 was enabled by soil water that likely accumulated from rains that fell in 2011 (Figure 6). The carbon sequestration rate we measured at the MCAGCC is within the range of other published studies: -106±69 g C m^{-2} $year^{-1}$ (2005 and 2006 average carbon sequestration) for a Mojave Desert shrubland (Wohlfahrt *et al.*, 2008), -127±17 g C m^{-2} $year^{-1}$ for a Mojave Desert shrubland (Jasoni *et al.*, 2005), -46 g C m^{-2} $year^{-1}$ (2002 and 2003 average carbon sequestration) for a Baja California shrubland (Hastings *et al.*, 2005), and -212 g C m^{-2} $year^{-1}$ for a semiarid shrubland in Arizona (Scott *et al.*, 2006). Statistically significant regression line slopes (Figure 7) suggest that air and soil temperatures, PFD, net radiation, and soil water content all modulated NEE to some degree. As air temperature, soil temperature, PAR, and net radiation increased, NEE became more negative (more CO_2 uptake). As air temperature, soil temperature, PAR, and net radiation increased, NEE became more negative (more CO_2 uptake). Increasing soil moisture had an opposite effect—

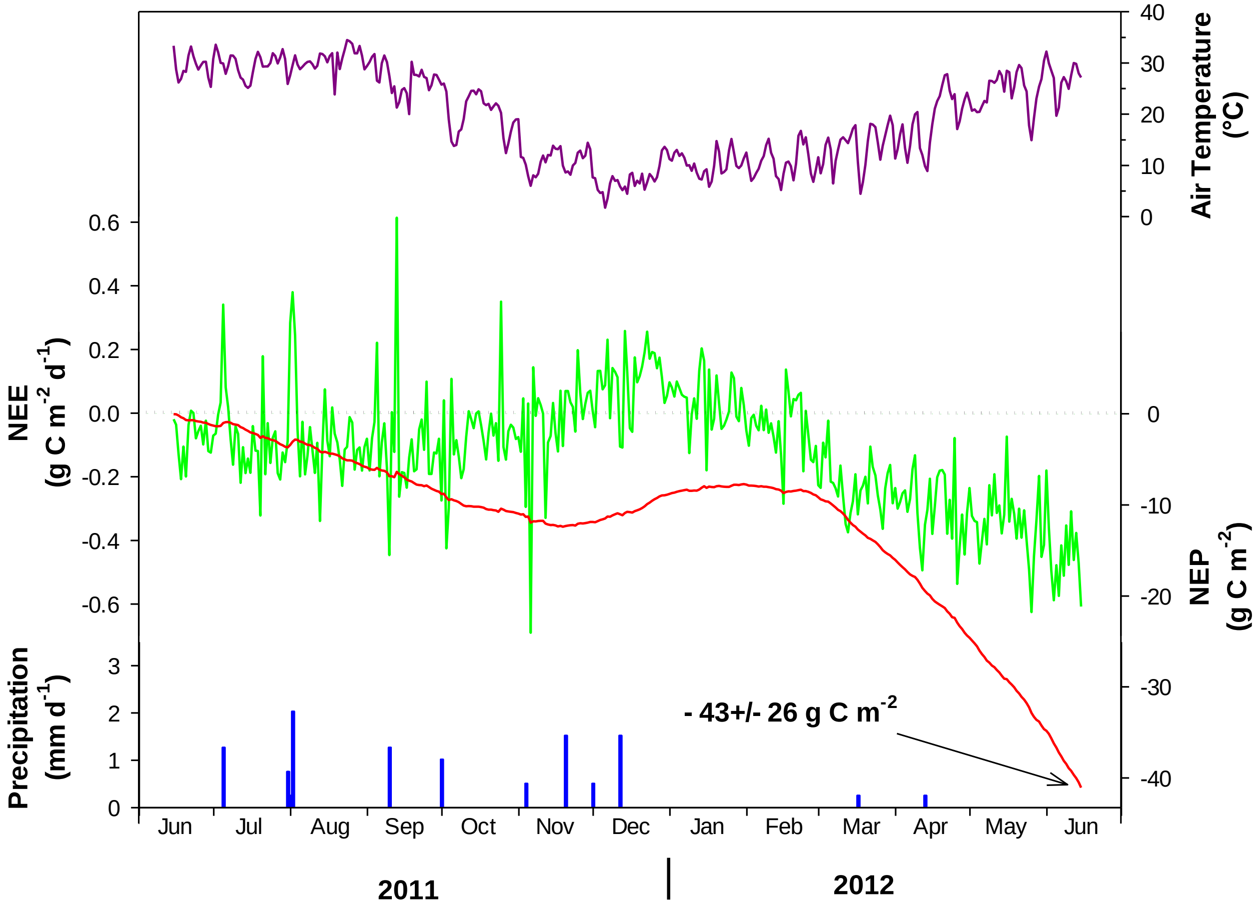

Figure 6. Net ecosystem productivity (NEP, cumulative sum of NEE) (red line), net ecosystem CO_2flux (NEE) (green line), mean daily air temperature (purple line) and daily precipitation (blue bars) measured at the Marine Corps Air Ground Combat Center (MCAGCC) measured between June 15, 2011 and June 15, 2012.

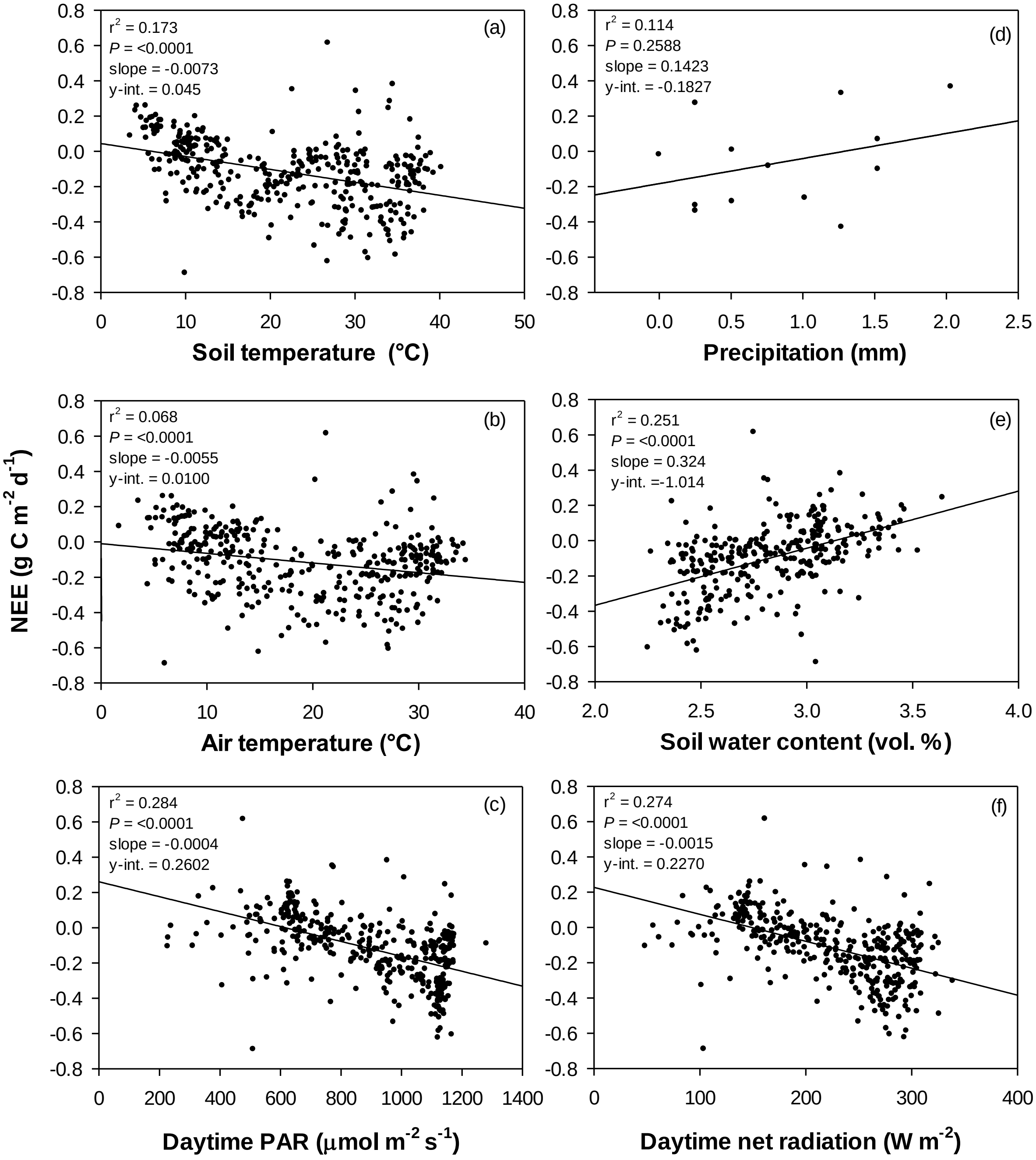

Figure 7. Regression analysis of daily sums of net ecosystem exchange (NEE) vs. (a) soil temperature, (b) air temperature, (c) daytimePAR flux density (PFD), (d) precipitation, (e) soil water content, and (f) daytime net radiation measured at the Marine Corps Air Ground Combat Center (MCAGCC) between June 15, 2011 and June 15, 2012.

especially following rains—on ecosystem CO_2 uptake (Figure 8), apparently promoting the activity of heterotrophic microorganisms (and heterotrophic respiration: R_h) more than the activity of plants (Huxman *et al*. 2004) and autotrophic crust organisms. Large CO_2 effluxes occurring immediately after rains in the warm seasons of 2011 (less so in winter months, Figure 8) indeed suggest that this precipitation only infiltrated the topmost layers of the soil, stimulating R_h more than plant photosynthesis. The larger negative NEE values (net CO_2 uptake) and faster accumulation of ecosystem C measured in late winter through spring and summer of 2012, relative to the less negative values observed in the summer of 2011, may have been due at least in part to the absence of large post-rainfall CO_2 efflux events in 2012 (i.e, so few rains in 2012). The lack of any such efflux events in 2012 following rains may have been due to the low amounts that fell, even though large efflux pulses have been observed during rains that fall on particularly dry soils (Wohlfahrt *et* al. 2008; Hastings *et al*. 2005, Veenendaal *et al*. 2005; Xu and Baldocchi 2003).

Quantification of NEE in arid environments using open path infrared gas analyzers IRGAs) can be difficult because of the uncertainties associated with parameters used in the density correction calculation; therefore, the resulting total systematic uncertainties in arid environments tend to be large. The main cause for these large uncertainties in arid environments is the low CO_2 fluxes and the large density corrections that are needed because of large sensible heat fluxes (Webb *et al.,* 1980). To partially overcome these challenges the EC instrumentation must be maintained regularly, appropriately calibrated before deployment, and data properly analyzed (especially frequency response corrections). During this one-year study, we had a sensor maintenance schedule which included monthly cleaning and checking of all instrumentation that kept all sensors at the highest level of functionality. Data also were analyzed using the most appropriate EC corrections and filtering procedures (see Materials and Methods section).

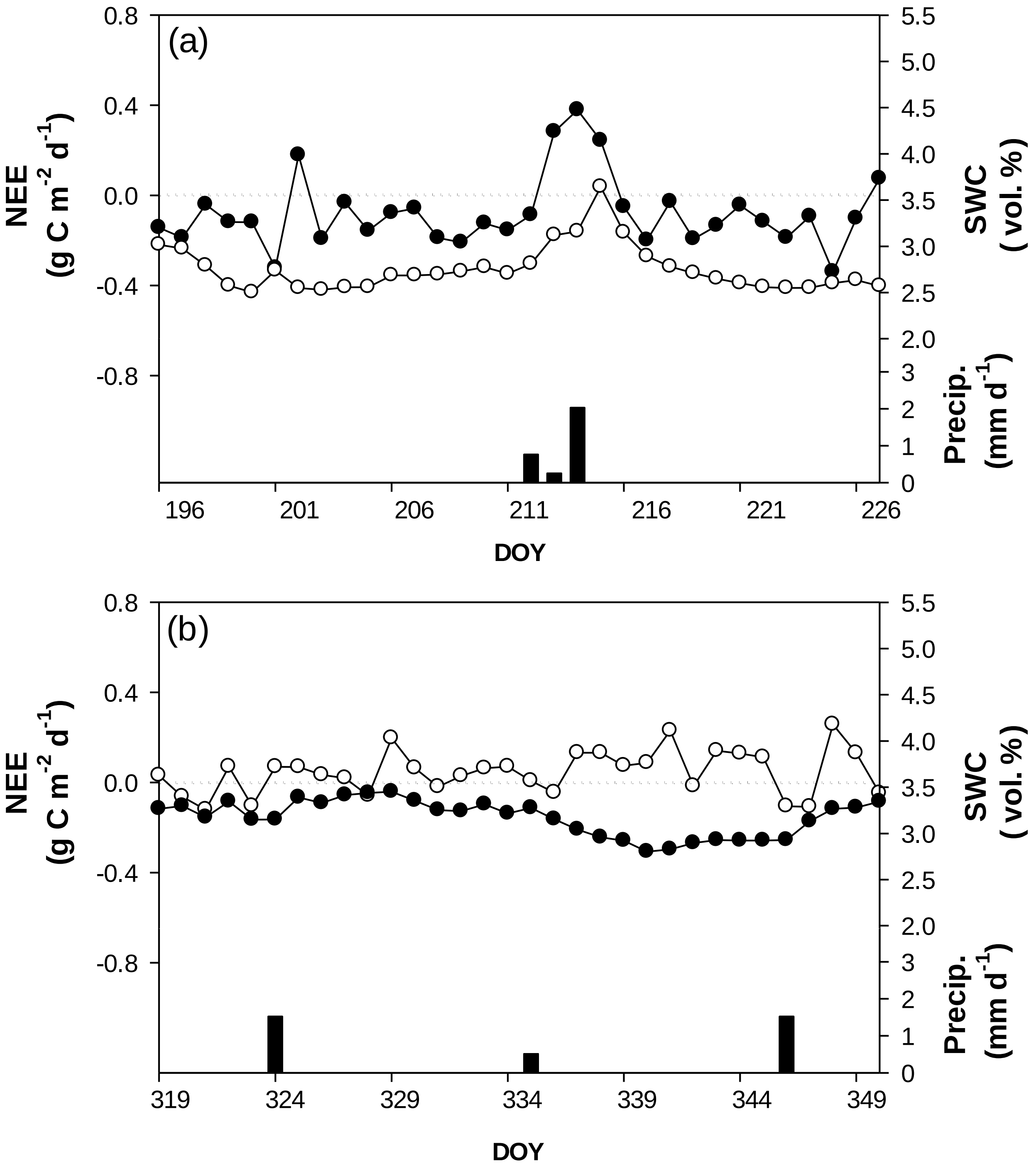

Figure 8. Thirty-day time series of daily sums of net ecosystem CO_2 exchange (NEE; filled symbols), daily precipitation (black bars), and daily average soil water content (SWC; open symbols) showing precipitation effects on NEE during the (a) summer (June 15 to August 15, 2011) and (b) late fall (November 16 to December 16, 2011) at the Marine Corps Air Ground Combat Center (MCAGCC).

Collectively, our results show that: (1) the Mojave Desert ecosystem situated at MCAGCC was a net sink for C on an annual basis and is within the range of other studies; (2) our choice of analysis methods were appropriate for use in an arid ecosystem; (3) seasonal variation in NEE, and therefore annual C sequestration, most likely depends on soil moisture conditions and precipitation, and their effects on plant, microbial, and soil biological crust activity; (4) low precipitation years might have lower annual C sequestration than years with average or above average precipitation, but with a possible lag (one to two years) in the response (higher carbon sequestration) to increased precipitation after prolonged drought conditions; and (5) arid shrublands similar to those found at the MCAGCC may play a significant role in modulating anthropogenic greenhouse gas emissions.

Land management options

It is possible to manage carbon within the biosphere by planting or removing vegetation and by managing soils. Increasing carbon stocks within the ecosystem can help reduce CO_2 concentrations within the atmosphere and store carbon within the ecosystem (within plants or soil). Increasing carbon stocks can have an immediate effect on atmospheric CO_2 concentration, however, lower atmospheric CO_2 concentration reduces the natural CO_2 uptake of oceans thus creating a feedback effect complicating the apparent ease of planting more vegetation to mitigate anthropogenic CO_2 emissions. Most of the limitations to the use of vegetation to offset anthropogenic CO_2 emission are the result of the carbon-storage potential on any given area of land which can be rather small. Therefore, in order to maximize the atmospheric mitigation potential of vegetation or soils the feedback effects need to be considered before deciding on the optimal mitigation strategy. Overall, mitigation of anthropogenic CO_2 within the atmosphere by vegetation is possible, and can play a useful role in mitigating atmospheric CO_2 concentrations, even if the impact is small. However, the most practical long-term solution to reducing large amounts of CO_2 in the atmosphere is to reduce fossil fuel emissions. Conversion from fossil fuels to alternative energy sources will directly reduce atmospheric CO_2 concentration. Although a combined approach using alternative energy sources and vegetation/soil approaches may effectively reduce atmospheric CO_2 concentrations.

Offset projects are quantified under regulatory protocols that are approved by the Board and must meet the AB 32 offset criteria of being real, additional, quantifiable, permanent, verifiable, and enforceable. ARB has approved offset protocols for four project areas: forestry, urban forestry, livestock digesters, and the destruction of ozone depleting substances. ARB accredits third-party verifiers to independently verify all offset project reports. Accredited third-party verifiers have extensive backgrounds in related areas, including appropriate field and auditing experience, as well as the scientific and engineering knowledge required for verification. Third-party verifiers must work through ARB accredited verification bodies and must complete ARB's training and pass a specialized test.

Issues

There are two potential drawbacks to drawing conclusions from a short-term, or "snapshot" study such as described in this report. Firstly, year-to-year variability in climate can alter CO_2fluxes and can change fluxes from net sinks to net sources. Secondly, biological soil crusts and disturbance – both of which occur on site, can reduce C sequestration.

However, making carbon flux measurements for multiple years, and even possibly at multiple sites would to some extent mitigate the variability in climate and its impact on the data. An evaluation of soil carbon would provide input for more thorough quantification of carbon sequestration, although disturbance levels may vary which would again result in data of a snapshot nature.

Conducting ecosystem modeling with our existing data would help to more accurately determine carbon flux at MCAGCC scales, and would provide some solutions to the issues described above.

Summary

Project results indicated that inspite of a low precipitation year, the land surface of the Marine Corps Air Ground Combat Center (MCAGCC) sequestered a significant amount of $CO_{2.}$

Arid ecosystems cover a significant amount of the Earth's terrestrial land surface and can play a significant role in modulating atmospheric CO_2 concentrations. Net ecosystem CO_2 exchange was measured for a one year period at MCAGCC near TwentyninePalms, CA using the eddy covariance (EC) method. Annual C sequestration was -43±26 g C m^{-2} $year^{-1}$(note: a negative value, in this case "-43, indicates sequestration of carbon), making the MCAGCC a net sink for CO_2 during the one year measurement period. Daily net ecosystem CO_2 exchange(NEE) during the one year study varied, but overall, CO_2 uptake occurred for the majority of the year. There was a brief period of time between late November 2011 and mid-January 2012 when there was an overall release of CO_2 to the atmosphere with an average release of 0.1 g C m^{-2} d^{-1}. The highest uptake rates were observed between March and June 2012 with an average uptake of -0.3 g C m^{-2} d^{-1}. The lowest uptake rates occurred between June and November 2011, with daily NEE remaining relatively consistent during this time period with an average rate of approximately -0.1 g C m^{-2} d^{-1}. Daily NEE for the one year study ranged from a release of 0.6g C m^{-2} $d^{-1}$to an uptake of -0.7 g C m^{-2} d^{-1}. Average daily NEE during the one year study was -0.1 g C m^{-2} d^{-1}. Spikes in NEE occurred during or immediately after rainfall. Very little precipitation fell during the one year study period which most likely had a significant impact on C sequestration. Years with higher precipitation may lead to higher C sequestration values because of a greater stimulation of plant photosynthesis. Results indicate that arid shrublands similar to those found at the MCAGCC may play a significant role in modulating anthropogenic greenhouse gas emissions.

Acknowledgements

The authors wish to acknowledge the United States Marine Corps for contract # W911NF-09-1-0560 issued through the Army Research Office to the Desert Research Institute. We further wish to acknowledge a number of individuals and organizations who greatly assisted this research project. Tom Decosta and Stan Norquist, with Marine Corps Installations West, provided encouragement, support, and ideas and suggestions. The Marine Corps Air Ground Combat Center (MCAGCC), assisted in numerous ways with ideas and field support. MCAGCC further arranged for a helicopter flight with Mercy Air Services which provided invaluable land cover information.

References

Albaladejo, J., M. Stocking, E. Dõas and V. Castillo, 1994. Land rehabilitation by urban refuse amendments in a semi-arid environment: effect on soil chemical properties. Soil Technology, 7: 249-260.

Arnone, J.A.A., P.S.J. Verburg, D.W. Johnson et al., 2008. Prolonged suppression of ecosystem carbon dioxide uptake after an anomalously warm year. Nature, DOI: 10.1038/nature07296.

Aubinet, M., A. Grelle, A. Ibrom et al., 2000. Estimates of the annual net carbon and water exchange of forest: the EUROFLUX methodology. Advances in Ecological Research, 30: 113–175.

Aubinet, M., B. Chermanne, M. Vandenhaute, B. Longdoz, M. Yernaux and E. Laitat, 2001. Long term carbon dioxide exchange above a mixed forest in the Belgian Ardennes. Agricultural and Forest Meteorology, 108: 293–315.

Baldocchi, D.D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Global Change Biology, 9: 479-492.

Belnap J., S.L. Phillips and M.E. Miller, 2004. Response of desert biological soil crusts to alterations in precipitation frequency. Oecologia, 141: 306–316.

Beltrán, J. M., 1999. Irrigation with saline water: benefits and environmental impact. Journal of Agricultural Water Management, 40: 183-194.

Bestelmeyer, B.T., D.A. Trujillo, A.J. Tugel and K.M. Havstad, 2006. A multi-scale classification of vegetation dynamics in arid lands: What is the right scale for models, monitoring and restoration? Journal of Arid Environments, 65: 296-318.

Bunce, J.A., 1982. Low humidity effects on photosynthesis in single leaves of C-4 plants. Oecologia, 54: 233-235.

CA Dept. of Water Resources, 2003. California's Groundwater Bulletin 118. California Department of Water Resources. http://www.water.ca.gov/groundwater/bulletin118/gwbasin_maps_descriptions.cfm

CEQ (Council on Environmental Quality), 2010. Draft NEPA guidance on consideration of the effects of climate change and greenhouse gas emissions. Memorandum for heads of federal departments and agencies, February 18, 2010.

Cooper, C., Ed., 2009. A Technical Basis for Carbon Dioxide Storage; Report. Prepared by members of the CO_2 Capture Project.

DOE, 1999. Carbon Sequestration State of the Science: A working paper for roadmapping future carbon sequestration R&D; Paper. U.S. Department of Energy.

DOE/NETL, 2011. Coal-Fired Power Plants in the United States: Examination of the Costs of Retrofitting with CO_2 Capture Technology, Revision 3; Report. U.S. Department of Energy's National Energy Technology Laboratory.

Emmerich, W.E., 2003 Carbon dioxide fluxes in a semiarid environment with high carbonate soils. Agricultural and Forest Meteorology, 116: 91–102.

Evans, R.D. and J.R. Johansen, 1999. Microbiotic crusts and ecosystem processes. Critical Review in Plant Sciences, 18: 183–225.

Falge, E., D. Baldocchi, R.J. Olson, et al., 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agricultural and Forest Meteorology, 107: 43–69.

Falge, E., D. Baldocchi, J. Tenhunen et al., 2002a. Phase and amplitude of ecosystem carbon release and uptake potential as derived from FLUXNET measurements. Agricultural and Forest Meteorology, 113: 75–95.

Falge, E., D. Baldocchi, J. Tenhunen et al., 2002b. Seasonality of ecosystem respiration and gross primary production as derived from FLUXNET measurements. Agricultural and Forest Meteorology, 113: 53–74.

Foken, Th., M. Göckede, M. Mauder, L. Mahrt, B. Amiro and W. Munger, 2004. Post-field data quality control. In: Handbook of Micrometeorology (eds X. Lee, W. Massman and B. Law), pp. 181–208. Kluwer Academic Publishers, Dordrecht.

Foken. Th. And B. Wichura, 1996. Tools for quality assessment of surface-based flux measurements. Agricultural and Forest Meteorology, 78: 83–105.

Gash, J.H.C. and A.J. Dolman, 2003. Sonic anemometer (co)sine response and flux measurement I. potential for (co)sine error to affect sonic anemometer-based flux measurements. Agricultural and Forest Meteorology, 119: 195–207.

Geissbühler, P., R. Siegwolf and W. Eugster, 2000. Eddy covariance measurements on mountain slopes: the advantage of surface-normal sensor orientation over a vertical set-up. Boundary-Layer Meteorology, 96: 317–392.

Grace, J., 2004. Understanding and managing the global carbon cycle. Journal of Ecology, 92: 189–202.

Gu, L., E. Falge, T. Boden et al., 2005. Objective threshold determination for nighttime eddy flux filtering. Agricultural and Forest Meteorology, 128: 179–197.

Ham, J.M. and J.L. Heilman, 2003. Experimental test of density and energy-balance corrections on carbon dioxide flux as measured using open-path eddy covariance. Agronomy Journal, 95: 1393–1403.

Hastings, S.J., W.C.Oechel and A. Muhlia-Melo, 2005. Diurnal, seasonal and annual variation in the net ecosystem CO2 exchange of a desert shrub community (*Sarcocaulescent*) in Baja California, Mexico. Global Change Biology, 11: 927–939.

Havstad, K. M., R.P. Gibbens, C.A. Knorr and L.W.Murray, 1999. Long-term influences of shrub removal and lagomorph exclusion on Chihuahuan Desert vegetation dynamics. Journal of Arid Environments 42: 155-166.

Herberl, C.H., and R.P. Gibbens, 1996. Post-drought vegetation dynamics on arid rangelands in Southern New Mexico. New Mexico Agricultural Experiment Station Bulletin 776. 102pp.

Herrick, J.E., B.T. Bestelmeyer, S. Archer, A.J. Tugel and J.R. Brown, 2006. An integrated framework for science-based arid land management. Journal of Arid Environments, 65: 319-335.

Hsieh, C.I, G. Katul and T.W. Chi, 2000. An approximate analytical model for footprint estimation of scalar fluxes in thermally stratified atmospheric flows. Advances in Water Resources, 23: 765–772.

http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?catwen+sca; July 1, 1948 – December 31, 2005.

http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?catwen+sca; July 1, 1948 – December 31, 2005.

http://www.arb.ca.gov/cc/capandtrade/guidance/chapter6.pdf

ICF International, 2009. Developing a Pipeline Infrastructure for $C0_2$ Capture and Storage: Issues and Challenges, Paper Prepared for INGAA Foundation.

Jasoni, R.L., S.D. Smith and J.A. Arnone III, 2005. Net ecosystem CO_2 exchange in Mojave Desert shrublands during the eighth year of exposure to elevated CO_2. Global Change Biology, 11: 749-756.

Jordan, D.N., S.F. Zitzer, G.R. Hendrey, K.F. Lewin, J. Nagy, R.S. Nowak, S.D. Smith, J.S. Coleman and J.R. Seeman, 1999. Biotic, abiotic and performance aspects of the Nevada Desert Free-Air CO2 Enrichment (FACE) Facility. Global Change Biology, 5: 659-668.

Kaimal, J.C., and J.J. Finnigan, 1994. Atmospheric boundary layer flows: Their structure and measurement. Oxford University Press. New York, NY, p. 289.

Körner, C., 1994. In: *Ecology of Photosynthesis* (eds E.D. Schulze and M.M. Caldwell), pp. 463–490. Springer, Chicago, IL.

Lado, M. and M. Ben-Hur, 2009. Treated domestic sewage irrigation effects on soil hydraulic properties in arid and semiarid zones: A review. Journal of Soil and Tillage Research, 106: 152-163.

Lal, R., 2004. Carbon sequestration in dryland ecosystems. Environmental Management, 33: 528–544.

Larcher, W., 2001. Physiological Plant Ecology. Ulmer Verlag, Stuttgart.

Law, B.E., E. Falge, L. Gu et al., 2002. Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation. Agricultural and Forest Meteorology, 113: 97–120.

Lee, X., J. Finnigan and U.K.T. Paw, 2004. Coordinate systems and flux bias error. In: Handbook of Micrometeorology (eds X. Lee, W. Massman and B. Law), pp. 33–66. Kluwer Academic Publishers, Dordrecht.

Loescher, H.W., T. Ocheltree, B. Tanner et al., 2005. Comparison of temperature and wind statistics in contrasting environments among different sonic anemometer-thermometers. Agricultural and Forest Meteorology, 133: 119–139.

Luo, H., W.C. Oechel, S.J. Hastings, R. Zulueta, Y. Qian and H. Kwon, 2007. Mature semiarid chaparral ecosystems can be a significant sink for atmospheric carbon dioxide. Global Change Biology, 13: 386–396.

Massman, W.J., 2000. A simple method for estimating frequency response corrections for eddy covariance systems. Agricultural and Forest Meteorology, 104: 185–198.

Massman, W.J., 2001. Reply to comment by Rannik on ‘‘A simple method for estimating frequency response corrections for eddy covariance systems’’. Agricultural and Forest Meteorology, 107: 247–251.

Massman, W.J. and R. Clement, 2004. Uncertainty in eddy covariance flux estimates resulting from spectral attenuation. In: Handbook of Micrometeorology (eds X. Lee, W. Massman and B. Law), pp. 67–100. Kluwer Academic Publishers, Dordrecht.

Massman, W.J. and X. Lee, 2002. Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges. Agricultural and Forest Meteorology, 113: 121–144.

MIT, 2007. The Future of Coal. An Interdisciplinary Massachusetts Institute of Technology Study.

Miyamoto, S., E.P. Gleen and M.W. Olsen, 1996. Growth, water use and salt uptake of four halophytes irrigated with highly saline water. Journal of Arid Environments, 32: 141-159.

Moffat, A.M., D. Papale, M. Reichstein et al., 2007. Comprehensive comparison of gap-filling techniques for eddy covariance net carbon fluxes. Agricultural and Forest Meteorology, 147: 209–232.

Mouat, D.A., 1974. Relationships between vegetation and terrain variables in southeastern Arizona. Ph.D. Dissertation, Oregon State University.

Navas, A., J. Machõn and B. Navas, 1999. Use of biosolids to restore the natural vegetation cover on degraded soils in the badlands of Zaragoza (NE Spain). Bioresource Technology, 69: 199-205.

NETL, 2010. Carbon Sequestration Atlas of the United States and Canada, Third Edition. U.S. Department of Energy's National Energy Technology Laboratory.

NETL, 2010. Carbon Storage Program. U.S. Department of Energy's National Energy Technology Laboratory. http://www.netl.doe.gov/technologies/carbon_seq/overview.html

NETL, 2010. *DOE/NETL* Carbon Dioxide Capture and Storage RD&D Roadmap; Report. U.S. Department of Energy's National Energy Technology Laboratory.

Okin, G., B. Murray and W. Schlesinger, 2001. Degradation of Sandy Arid Shrubland Environments: Observations, Process Modeling, and Management Implications. Journal of Arid Environments, 47: 123-144.

Oren, R., J.S. Sperry, G.G. Katul et al., 1999. Survey and synthesis of intra- and interspecific variation in stomatal sensitivity to vapour pressure deficit. Plant Cell & Environment, 22: 1515–1526.

Rubin, E., C. Chen, and A. Rao, 2007. Cost and Performance of Fossil Fuel Power Plants with CO2 Capture and Storage. Energy Policy, 35: 4444-4454.

Schlesinger, W. H., J. Belnap and G. Marion, 2009. On carbon sequestration in desert ecosystems. Global Change Biology, 15: 1488-1490.

Scott, R. L., T.E. Huxman, D.G. Williams and D.C. Goodrich, 2006. Ecohydrological impacts of woody-plant encroachment: seasonal patterns of water and carbon dioxide exchange within a semiarid riparian environment. Global Change Biology, 12: 311-324.

Scott, R.L., T.E. Huxman, D.G. Williams and D.C. Goodrich, 2006. Ecohydrological impacts of woody plant encroachment: seasonal patterns of water and carbon dioxide exchange within a semiarid riparian environment. Global Change Biology, 12: 311–324.

Unkefer, P. J., M. H. Ebinger, D. D. Breshears, T. J. Knight, C. L. Kitts and S. A. VanOoteghem. 2001. Native Plants for Optimizing Carbon Sequestration in Reclaimed Lands. Journal of Energy & Environmental Research, 1(2): 127-135.

Veenendaal, E.M., O. Kolle and J. Lloyd, 2004. Seasonal variation in energy fluxes and carbon dioxide exchange for a broad-leaved semi-arid savanna (Mopane woodland) in Southern Africa. Global Change Biology, 10: 318–328.

Watts, S.E., 1998. Short-term influence of tank tracks on vegetation and microphytic crust in shrubsteppe habitat. Environmental Management, 22: 611-616.

Webb, R.H., M.B. Murov, T.C. Esque et al., 2003. Perennial vegetation data from permanent plots on the Nevada Test Site, Nye County, Nevada. US Geological Survey Open-File Report 03–336 (http://www.werc.usgs.gov/lasvegas/ofr-03-336.html).

Webb, E.K, G.I. Pearman and R. Leuning, 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Quarterly Journal of the Royal Meteorological Society, 106: 85–100.

Wohlfahrt, G., C. Anfang, M. Bahn et al., 2005. Quantifying nighttime ecosystem respiration of a meadow using eddy covariance, chambers and modeling. Agricultural and Forest Meteorology, 128: 141–162.

Wohlfahrt, G., L.F. Fenstermaker and J.A. Arnone III, 2008. Large annual net ecosystem CO_2 uptake of a Mojave Desert ecosystem. Global Change Biology, 14: 1475-1487.

Xie, Y., Z. Sha and M. Yu, 2008. Remote sensing imagery in vegetation mapping: a review. Journal of Plant Ecology, 1 (1): 9-23.

Xu, L. and D.D. Baldocchi, 2003. Seasonal variation in carbon dioxide exchange over a Mediterranean annual grassland in California. Agricultural and Forest Meteorology, 123: 79–96.

Appendix A

Potential cost of doing carbon capture and sequestration and storage for the MCAGCC cogeneration plant.

GHG mitigation at the cogeneration plants could theoretically be augmented through the use of emerging carbon capture and sequestration (CCS) technologies, if local geology is favorable. Recent International Energy Agency data(1) indicate that overnight(2) costs for post combustion CO2 capture (capture only, excludes transport and storage of CO2) from natural gas combined cycles ranges from $2,502 to $3,776 U.S. dollars in 2010 (USD 2010) per kilowatt output capacity at average CO2 capture rates of 87%. These data were generated for plants with non-CO2 capture output capacities ranging from 395 to 776 MW. Linear extrapolation of this data set to a 16.2 MW size provides a rough estimate of overnight(2) cost (capture only, excluding transport and storage of CO2) of CCS applied to both MCAGCC cogeneration plants ranging from $40 to $60 million USD 2010. This indicates that CCS would not be a cost-effective strategy to address GHG emissions under AB 32. CHP facilities represent the most efficient source of baseloaded electricity available from current generating technologies. No source of power could provide the reliable supply that is available from the CHP plants at MCAGCC with a cleaner GHG and air quality profile. (MCAGCC ISAP draft final Nov 2012)

(1) International Energy Agency, 2011. "Cost and Performance of Carbon Dioxide Capture from Power Generation". Paris, France.
(2) Overnight costs assume the power plant could be constructed in a single day. They reflect technological and engineering costs in a particular country but avoid impacts of the specific financial structure that is in place to realize construction. While for real projects investors need to pay close attention to total capital requirements, overnight costs are useful in particular to energy scenario modelers, policy makers and utilities for comparisons of cost at an early stage of assessment.

Appendix B

Eddy covariance calculations

Eddy fluxes were calculated as the covariance between turbulent fluctuations of the vertical wind speed and CO_2 molar density derived from Reynolds (block) averaging of 30-min blocks of data. The sonic anemometer's coordinate system was numerically rotated during each averaging period by applying a double rotation, aligning the longitudinal wind component into the main wind direction, and forcing the mean vertical wind speed to zero (Kaimal and Finnigan, 1994; Wohlfahrt *et al.,* 2008). Frequency response corrections were applied to raw eddy fluxes accounting for low-pass (lateral and longitudinal sensor separation, sensor time response, scalar and vector path averaging) and high-pass (block averaging) filtering (Massman, 2000, 2001) using a site-specific, co-spectral reference model (Massman and Clement, 2004; Wohlfahrt *et al.,*2005). Experimentally-derived frequency response correction factors (Aubinet *et al.*, 2000, 2001) were used to assess the validity of the theoretical low-pass filtering correction method as detailed in Wohlfahrt *et al.,* (2005). Fluxes also were corrected for the effect of air density fluctuations following Webb *et al.,* (1980). Finally, CO_2 fluxes were analyzed for biases due to low and high turbulence (Gu*et al.,* 2005) (Figure 4). Night time respiration was independent of friction velocity (μ^*) (friction velocity is a measure of turbulent mixing) between 0.03 and 0.55 m s^{-1} (Figure 4). Flux measurements below or above this threshold indicate advection and pressure-pumping, respectively (Wohlfahrt *et al.*, 2008; Massman and Lee 2002) both of which can cause flux underestimation during periods of low turbulence, and therefore errors in night time respiration values. Errors during periods of low turbulence can lead to inaccuracies in CO_2 balance calculations; therefore, flux data were excluded when μ^* was outside of the 0.03 and 0.55 m s^{-1} range.

Half-hourly flux data were quality controlled in a five-step filtering procedure. First, periods were identified when the EC system was not working properly because of adverse environmental conditions (usually rain or snow) or instrument malfunction. Second, half-hourly values that were comprised of less than the full complement of measured values (i.e., less than 18,000) were removed. Third, data were subjected to the integral turbulence test (Foken and Wichura, 1996) and accepted only on the condition that they did not exceed the target value (Foken *et al.*, 2004) by more than 60 percent (Wohlfahrt *et al.*, 2008). Fourth, data were subjected to the angle of attack test (β - beta; the angle between the wind vector and horizontal), which identifies errors in data resulting from the imperfect cosine response of sonic anemometers. Data were excluded when the angle of attack was greater than 20º (Geissbühler *et al.*, 2000; Gash and Dolman, 2003). Finally, data were excluded when the automatic gain control (AGC) of the IRGA was greater than 10percentof the specific baseline value for each instrument. Increases from baseline AGC typically result from rain, snow, or ice accumulation on the surface of the lens of the IRGA and result in errors in water vapor density values.

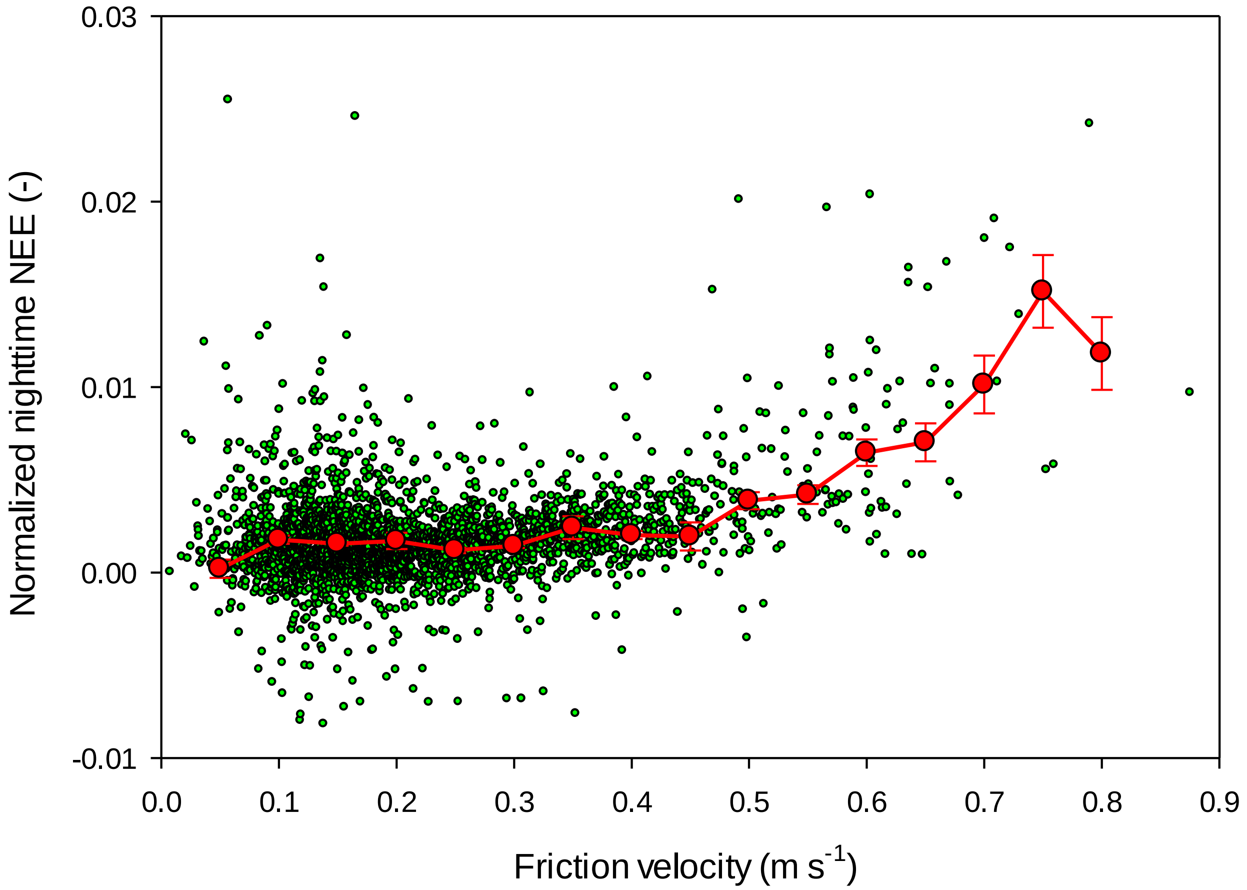

Figure 4. Night time ecosystem respiration normalized with a parametric model relating soil temperature to ecosystem respiration, as a function of friction velocity. Green circles represent half-hourly data from June 15, 2011 to June 15, 2012, red circles (with line between) represent bin-averages (0.5 m s^{-1} bins) of normalized night time NEE. Error bars are ± standard error.

Appendix C

Gap filling and systematic uncertainty analysis

The following gap filling procedure was performed in order to obtain continuous NEE values and to calculate annual C sequestration. Data gaps (30-min time steps; both daytime and night time values), resulting from filtering or missing data, were filled using the mean diurnal variation method with a time window of one month (Wohlfahrt *et al.*, 2008; Falge *et al.*, 2001). The mean diurnal variation method has been shown to be very accurate (Wohlfahrt *et al.*, 2008; Moffat *et al.*, 2007) and therefore we did not attempt any other gap filling methods.

Systematic uncertainty of CO_2 estimates derive primarily from the collective effects of inherent instrument measurement errors on density corrections (Webb *et al.*, 1980; Webb, Pearman and Leuning Correction [WPL]). Uncertainty introduced by applying the WPL correction under the range of inherent measurement errors for each instrument (sensor) was estimated by defining a likely relative uncertainty for each independent parameter (instrument measurement) and by applying this, in turn, to calculate annual NEP. Assuming that the various component uncertainties are independent, the combined uncertainty from the WPL correction was calculated by taking the square root of the sum of the squared individual uncertainties. Based on manufacturers' specifications, and on past experience with long-term sensor stability, the water vapor density, and static air pressure were assigned uncertainties of 10 percent (Wohlfahrt *et al.*, 2008) while air temperature was assigned an uncertainty of two percent. Uncertainty in the sensible heat flux may arise from the fact that the sensible heat flux was measured based on speed of sound measurements, which has been shown by Loescher *et al.*, (2005) to deviate from sensible heat flux derived from measurements of air temperature with a fast-response platinum resistance thermometer by up to 10 percent for this specific sonic anemometer model. Alternatively, Ham and Heilman (2003) -again for the same anemometer model used in this study - found extremely close correspondence between sonic- and thermocouple-derived sensible heat flux measurements. Additional uncertainty of the sensible heat flux arises from the choice of coordinate system (Lee *et al.*, 2004) and from the necessary (small) frequency response corrections (Massman 2001).Based on the research findings presented above and some preliminary sensitivity tests with different coordinate systems (data not shown), a five percent uncertainty for the sensible heat flux was assumed. Similar to the sensible heat flux, a five percent uncertainty for latent heat flux was assumed, intended to reflect uncertainties because of choice of the coordinate system and frequency response corrections, which are based on a site-specific co-spectral reference model (cf. Massman and Clement, 2004; Wohlfahrt*et al.*, 2005) and have been validated against experimentally derived frequency response correction factors following Aubinet *et al.*, (2000) and Aubinet *et al.*, (2001) as described in Wohlfahrt *et al.*, (2005) and Wohlfahrt *et al.*, (2008). Based on this information, five percent uncertainty is justified and not nearly as large as the upper range of potential errors in frequency response correction factors (30 percent) reported by Massman and Clement (2004).

Appendix D

Measurement footprint analysis

The area of the measurement footprint was calculated using the footprint model of Hsieh *et al.*, (2000) to estimate the upwind distance and compass direction that represented 90 percent of the surface flux for each half-hour period ($X_{90\%}$). Close agreement between modelled and measured data from arid and agricultural areas has shown the model to be valid and provides reliable footprint data (Hsieh *et al.*, 2000).

$$X_{90\%} = \frac{-D|L|^{(1-P)}\,Z_u^P}{k^2 \ln(0.90)} \qquad \text{Eq. 1}$$

Where k is the von Karman constant (0.4), L is the Obukhov length, and Z_u is the length scale calculated as:

$$Z_u = \frac{Z_m\,u\,k}{u_*} \qquad \text{Eq. 2}$$

Where Z_m is the measurement height, u is the mean wind speed, and D and P are stability-dependent coefficients:

$D = 0.28$; $P = 0.59$ for unstable conditions ($Z_u/L < -0.04$)

$D = 0.97$; $P = 1.00$ for near-neutral conditions ($-0.04 < Z_u/L < 0.04$)

$D = 2.44$; $P = 1.33$ for stable conditions ($Z_u/L > 0.04$)

Each calculated point, or footprint distance and direction (that corresponds to an individual 30-min CO_2 flux value), was then plotted in ArcGIS and a polygon circumscribed on the outside of the collective set of points that represented the footprint. Net ecosystem productivity for the footprint was then calculated using NEE values that were within the polygon. Net ecosystem efflux values that were removed during this process were gap filled using the gap filling method previously described.