

INVESTIGATION OF THE CARBON DIOXIDE EXCHANGE OVER A LIVING ROOF IN SAN FRANCISCO

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In

Geography: Resource Management and Environmental Planning

by

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San Francisco, California

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CERTIFICATION OF APPROVAL

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INVESTIGATION OF THE CARBON DIOXIDE EXCHANGE OVER A LIVING ROOF IN SAN FRANCISCO

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San Francisco, California
2016

Urban surfaces have been shown to be significant sources of atmospheric CO₂ up to 10 kg m⁻² a⁻¹ compared to natural ecosystems that tend to be sinks of about 0.1 to 1 kg m⁻² a⁻¹. Living roofs have the potential to help offset urban CO₂ emissions through sequestration of atmospheric CO₂ into the living biomass and soil, but their net ecosystem exchange (NEE) is largely unknown to date. This paper presents results from one year of eddy covariance derived CO₂ fluxes over a one-hectare living roof on the California Academy of Sciences Building in San Francisco, CA. The roof CO₂ fluxes corresponded closely with ecosystem functioning, producing a sink peaking at ~-0.2 mg C m⁻² s⁻¹ during daylight hours and a weak source of 0.1-0.2 mg C m⁻² s⁻¹ during the night. Monthly average daily NEE showed significant seasonal patterns, becoming a weaker daily source or net sink in spring, with daily values reaching -1.3 g C m⁻²d⁻¹ in May. Like natural ecosystems, the roof was a daily CO₂ sink during the growth period, but a much higher daily source during the pre-growth and dry periods (-1.1, 3.7, and 4.3 g C m⁻²d⁻¹). During all months of the year, a distinct asymmetric diurnal cycle was observed, suggesting that CO₂ sources from the building below may have caused the unnatural pattern. Even though the living roof was a net annual source of CO₂ of 1235 g C m⁻²a⁻¹, it may have had a mitigating effect and helped offset anthropogenic CO₂ emissions to a certain degree.

I certify that the Abstract is a correct representation of the content of this thesis.

Chair, Thesis Committee

Date

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1.0 BACKGROUND AND INTRODUCTION

1.1 Urban Carbon Dioxide Production and Mitigation Possibility of Living Roofs

With the steady geographic expansion of urban areas to accommodate a growing population, urban landscapes increasingly affect the global carbon dioxide exchange as large proportions of carbon dioxide (CO₂) emissions are produced within the complex urban ecosystem. Urban surfaces have been found to be significant sources of atmospheric CO₂ with magnitudes of 1-10 kg m⁻² a⁻¹ (Velasco and Roth, 2011) in comparison to natural ecosystems that tend to be carbon dioxide sinks with magnitudes of 0.1 to 1 kg m⁻² a⁻¹ (Baldocchi, 2008). Similar to natural ecosystems, urban parks and other types of greenspaces sequester and store carbon dioxide in the living biomass and soil, thereby partially mitigating anthropogenic produced CO₂ emissions (Kordowski and Kuttler, 2010). Living roofs or vegetated roofs represent a possibility to incorporate vegetation in urban planning to help offset urban CO₂ emissions. Living roofs have been touted for their benefits of storm water runoff mitigation and building temperature regulation, have been recognized as a way to reduce the urban heat-island effect and expand urban wildlife habitat (Oberndorfer et al., 2007). The potential for carbon dioxide sequestration of living roofs however, has not yet been widely explored. Their net ecosystem exchange, which is the balance between ecosystem photosynthesis and

respiration, is largely unknown, but short-term studies provide promising data that living roofs can act as a carbon sink (Thorp, 2014).

The location of the living roof ecosystem in an urban area, on the roof of the California Academy of Sciences (CAS) building in San Francisco, California, gives reason for the assumption that this ecosystem is a cross between urban and natural, and that it functions similar like certain elements of the urban and natural ecosystems. The following sections review the carbon dioxide exchange of urban and natural ecosystems comparable to the CAS living roof ecosystem, provide a brief history on living roofs and discuss their potential for carbon dioxide sequestration. The objective of this paper is to quantify diurnal, seasonal, and annual CO₂ exchanges between the living roof and the atmosphere, to determine whether the living roof is a CO₂ sink or source, and evaluate environmental controls on ecosystem functioning. Results from this study will help better understand how a living roof structure affects the local urban CO₂ exchange and how this feature could be used in urban planning for anthropogenic CO₂ mitigation.

1.2 Carbon Dioxide (CO₂) Exchange of Urban Ecosystems

Urban areas have a large impact on the global carbon dioxide exchange through locally produced greenhouse gas emissions from high-density anthropogenic activity and the alteration of the surface composition. The removal of vegetation changes the surface characteristics; natural ecosystems, functioning as net carbon dioxide sinks, are replaced

with non-vegetated impermeable surfaces, which may become net CO₂ sources. Even though urban areas represent only about 2% of the Earth's surface, they contribute more than 70% of the total anthropogenic CO₂ emissions (Canadell et al., 2009). Measuring CO₂ fluxes within urban environments is important to gain a better understanding of how anthropogenic factors affect the surface-atmosphere exchange of CO₂, causing CO₂ levels to be higher in urban than in non-urban environments.

Cities, from the point of view of the carbon cycle, can be thought of as an ecosystem with carbon sources from combustion of fossil fuels, buildings, and industrial and manufacturing processes, and carbon sinks from urban vegetation such as street trees, gardens, yards, as well as parks and playing fields. Urban vegetation sequesters CO₂ from the atmosphere during the day by photosynthesis, and releases some of the sequestered CO₂ through plant and soil respiration back into the atmosphere.

The net flux of CO₂ measured between the living roof and the atmosphere estimates the net ecosystem exchange (NEE). NEE can be broken down into its components of opposing signs, ecosystem photosynthesis or gross primary production (GPP) and respiration (RE). The balance between these two processes determines whether the ecosystem results in a net CO₂ sink or source.

The magnitudes of sources and sinks of the net urban carbon dioxide fluxes (F_{CO_2}) vary significantly between cities and even within cities since they are influenced by

population density, land use distribution, socio-economic and cultural aspects, local climate, and amount of vegetation (Velasco and Roth, 2010). Annual F_{CO_2} at urban sites can range from $361 \text{ g C m}^{-2} \text{ a}^{-1}$, as recorded in Baltimore, Maryland (Crawford et al., 2011), to $9,673 \text{ g C m}^{-2} \text{ a}^{-1}$ in London, England (Helfter et al., 2010). By micrometeorological convention, positive F_{CO_2} indicate a net carbon dioxide source and negative F_{CO_2} a carbon sink. Past research found a similarity in diurnal F_{CO_2} patterns within urban environments showing positive fluxes for most of the day (Velasco and Roth, 2010). On a seasonal timescale, wintertime F_{CO_2} can be more than twice as high as summer F_{CO_2} due to building heating and plant senescence (Matese et al., 2009; Pawlak et al., 2011). Helfter et al. (2011) recorded net emissions of CO_2 in London 20% higher in winter than in summer. In general, the largest F_{CO_2} are found in locations with highest building density and in city centers due to vehicular traffic and lowest vegetation fraction (Velasco and Roth, 2010).

Urban greenspace is an important mechanism to reduce levels of atmospheric carbon dioxide in dense urban environments. Impacts of vegetation on the urban CO_2 budget have been analyzed with a number of studies, the majority using vegetation stand inventories and a few utilizing the Eddy Covariance (EC) method (Jo and McPherson, 1995; Grimmond et al. 2002; Kordowski and Kuttler, 2010; Crawford et al., 2011). Jo and McPherson (1995) estimated biomass in northwest Chicago to quantify greenspace-

related carbon dioxide storage. Their findings showed that the difference of the size of the greenspace area and vegetation cover between two research sites, resulted in significant differences in total CO₂ storage and annual CO₂ uptake. The site with the higher vegetation fraction sequestered ~12% more CO₂ than the less vegetated site. Grimmond et al. (2002) used the Eddy Covariance method in a short-term study in a Chicago residential neighborhood and demonstrated that the study site with a 39% vegetated surface cover clearly sequestered CO₂ during the day but not enough to offset the anthropogenic CO₂ emissions. Similarly, long-term studies conducted using highly vegetated research sites (vegetation land-cover up to 67%) showed a marked daytime CO₂ uptake during summer but still remained a CO₂ source on an annual basis (Bergeron and Strachan, 2011; Crawford et al., 2011).

Urban parks can influence diurnal and seasonal F_{CO2} patterns by becoming temporary carbon sinks during summer. However, over the entirety of a year, these sites may turn into a weak source of CO₂ due to biogenic features (respiration), park maintenance (lawn mowing), and the close proximity of roads with high traffic density (Kordowski and Kuttler, 2010). Other greenspaces like sports arenas and agricultural fields within urban areas are similarly capable of slightly reducing CO₂ emissions by becoming small temporary sinks during the course of a day (Burri et al., 2009).

1.3 Living Roofs

Living roofs provide an opportunity to increase the vegetation fraction in urban environments and may serve as an emission offset strategy. According to Frazer (2005), roofs account up to 32% of the horizontal surface of built areas in a city and are important contributing factors of energy flux and water relations of buildings. Living or green roofs, also known as vegetative roofs or eco-roofs (roofs with a vegetated surface and substrate), provide many environmental benefits such as improved storm-water management, better regulation of building temperature, an expansion of urban wildlife habitat, and a reduction of the urban heat-island effect (Oberndorfer et al., 2007). However, research completed pertaining to living roofs' potential for offsetting CO₂ emissions in urban environments is scarce.

Roof gardens recorded in modern history date back to approximately 500 B.C. to the hanging gardens of Babylon, considered forerunners of contemporary living roofs (Getter and Rowe, 2006; Oberndorfer et al., 2007). Today, living roofs provide an attractive green space and are often used in building design for aesthetic reasons, or with a functional purpose to lower building heating or cooling needs, as well as to mitigate damaging physical effects such as fire hazards (Koehler and Keeley, 2005). The environmental benefits of living roofs first emerged in Germany at the turn of the 20th century (Koehler and Keeley, 2005). The technology developed rapidly there in the 1970s

due to growing environmental concerns in urban areas, creating opportunities for the introduction of progressive environmental thinking and technology (Dunnett and Kingsbury, 2004; Oberndorfer et al., 2007). Living roof technology has since been widely integrated in building construction in Germany (Haemmerle, 2002); an estimated 14% of all flat roofs are green (Koehler and Keeley, 2005). In Japan, Singapore, Germany, and Belgium the advantages of living roofs have been recognized and their use is encouraged with incentives or even imposed from the government (Dunnett and Kingsbury, 2004; Mentens et al., 2005). In Basel, Switzerland, green roof construction is enforced by legislation on newly built or renovated buildings with flat roofs (Brenneisen, 2006) (Figure 1). It is not yet a commonly used technology in the United States (Getter and Rowe, 2006).



Figure 1. Newly constructed green roof on the Klinikum 2 of the Cantonal Hospital of Basel, built in accordance with the city's new guidelines on green roofs and urban biodiversity. (Photo: Stephan Brenneisen)

The basic design of a modern living roof consists of a vegetation layer, a substrate layer in which vegetation is anchored and water retained, and a drainage layer through which excessive water runs off (Dunnett and Kingsbury, 2004; Getter and Rowe, 2006; Mentens et al., 2005). The depth of the substrate layer determines the roof type. The two main types distinguished are extensive and intensive living roofs. Extensive living roof systems have a shallower substrate (approximately up to 150 mm) than intensive roof gardens and require less maintenance (Dunnett and Kingsbury, 2004; Mentens et al., 2005; Getter and Rowe, 2006; Oberndorfer et al., 2007). According to Mentens et al. (2005), extensive living roofs may be installed on a sloped surface with an angle up to 45%. Plant species are typically limited to drought-tolerant succulents (e.g. Sedum) herbs, grasses, and mosses because of the shallow substrate (Mentens et al., 2005; Getter and Rowe, 2006). Intensive living roofs have a substrate layer with a depth larger than 150 mm, consist of grasses, perennial herbs and shrubs, are typically installed on roofs with a slope angle of less than 10%, and are more often used as roof gardens for aesthetic purposes, depending on design and access (Mentens et al., 2005).

1.4 Potential for Measuring Carbon Sequestration of Living Roofs

A small number of studies have been completed to quantify carbon storage potential of extensive living roofs using biomass sampling. Getter et al. (2009) evaluated 12 green roofs in Michigan, U.S.A. The magnitude of carbon sequestration was

determined over two growing seasons by sampling aboveground biomass of *Sedum* species, belowground biomass such as roots, and substrate carbon content. The entire living roof system stored 375 g C m^{-2} over two growing seasons (consisting of 168 g C m^{-2} in aboveground plant biomass, 107 g C m^{-2} in belowground plant biomass, and 100 g C m^{-2} in substrate carbon) (Getter et al., 2009). Biomass sampling provides useful information on annual carbon budget totals, but no information on diurnal or seasonal timeframes or environmental drivers of the carbon exchange (Thorp, 2014). The eddy covariance (EC) method on the contrary, can directly and continuously measure the CO_2 exchange of complex ecosystems and has extensively been utilized for long-term measurements of CO_2 budgets in forests, grasslands, and other natural environments (2001; Crawford et al., 2011). EC however, is much more difficult to apply in the complex urban environments and in particular, on a living roof. Drawbacks of the eddy covariance technique include that the study site must be relatively flat and of homogenous terrain to be measured accurately.

Li et al. (2010) used a LI-7500 gas analyzer (LI-COR Inc. Lincoln Nebraska) to observe CO_2 concentrations of four small plots of growing plants on the rooftop of a six-story building in Hong Kong. Specifically, one site was measured in the middle of the vegetated plot (P1) and the other site 2 m from vegetation (P2). The study was conducted over a period of two months during summer. The average value of CO_2

concentration was 700 mg/m^3 . P1 exhibited an average CO_2 concentration 12.9 mg/m^3 lower than P2 up to 17:00; thereafter, P1's CO_2 concentration was 4.9 mg/m^3 higher than P2s (Li et al., 2010). This study indicated the potential of rooftop plants to sequester CO_2 during daytime sunny conditions due to photosynthesis but also confirmed higher concentrations due to plant respiration at night. The difference in CO_2 observed between P1 and P2 however, greatly decreased with increasing airflow (Li et al., 2010). This method may have limits because it cannot distinguish CO_2 concentrations of two plots when the air mixes with increasing airflow.

Thorp (2014) made short-term observations of CO_2 fluxes during spring/summer using EC on the California Academy of Sciences (CAS) living roof in San Francisco, California, U.S.A. Gross primary production (GPP) over the three months study period was $-11.7 \text{ g C m}^{-2}\text{d}^{-1}$ which was found to be less than seasonal peaks of natural grasslands, croplands, and forests (Thorp, 2014). Respiration (RE) measured $+10.2 \text{ g C m}^{-2}\text{d}^{-1}$ was greater in contrast to many study sites of comparable natural ecosystems, which exhibit a range of seasonal maxima between $3.4\text{-}9.0 \text{ g C m}^{-2}\text{d}^{-1}$ according to Falge et al. (2002). This discrepancy may be attributed to the presence of a glass atrium, concrete viewing deck, small circular windows, and building vents on the living roof. Thorp (2014) concluded that all of these structures contributed carbon dioxide that was measured by EC (Thorp, 2014). Despite the uncertainty whether

anthropogenic sources were included in RE, it was determined that the site acted as a net CO₂ sink over the three month period with a ratio of magnitudes of (RE/GPP) of 0.87 and a CO₂ uptake of -1.5 g C m⁻²d⁻¹ (Thorp, 2014).

1.5 Natural Ecosystems comparable to CAS Living Roof Ecosystem

The study site for this research is the living roof of the California Academy of Sciences (CAS) building in San Francisco, California. The rooftop vegetation is composed of native local species from coastal scrub and north costal prairie communities of herbs, shrubs, and grasses (Figure 2). On an ecosystem level, natural ecosystems most closely resembling the roof ecosystem are semi-arid chaparral, shrub and grassland systems, and in particular Mediterranean chaparral and grassland ecosystems because the living roof is subject to a Mediterranean climate.



Figure 2. Vegetation vitality on the California Academy of Sciences living roof in San Francisco, CA, during the peak growing month, May 2015.

The growing seasons of grasslands in different climatic zones occur at different times of the year. Temperate grasslands, receiving precipitation throughout the year, usually begin CO₂ uptake with leaf emergence in spring, peak in summer, and gradually decrease production with leaf senescence (Flanagan et al., 2002). Semi-arid grassland ecosystems, subject to monsoon rains, are mostly dormant for the first part of the year and show a peak GPP around day 225 of the year, depending on when precipitation is received (Scott et al., 2010). Mediterranean chaparral, shrub, and grassland systems on the contrary, typically receive precipitation in late fall and winter, and exhibit a low GPP during winter, peaking in early spring, and decreasing in late spring with leaf senescence (Luo et al., 2007; Aires et al., 2008). These ecosystems are subject to dry and hot summers.

To date, temperate grassland systems have been more commonly studied than Mediterranean grassland sites (Xu and Baldocchi, 2004). Past research found that grassland ecosystems are sensitive to temporal variability in precipitation (Flanagan et al., 2002; Scott et al., 2010). Average and above-average precipitation received by temperate and semi-arid grassland ecosystems during the growing season typically produce CO₂ sinks on an annual basis (Flanagan et al., 2002; Scott et al., 2010). Magnitudes of CO₂ sequestered are in the range of -21 g C m⁻²a⁻¹ for a temperate grassland in Canada (Flanagan et al., 2002) and -55 g C m⁻²a⁻¹ for a semi-arid grassland

ecosystem in Arizona (Scott et al., 2010). The volatility of grassland ecosystems to precipitation becomes apparent when the annual precipitation received is less than average. An ecosystem may then change from a CO₂ sink to a CO₂ source (Flanagan et al., 2002; Scott et al., 2010). Net losses to the atmosphere of 18 g C m⁻²a⁻¹ have been reported at a temperate grassland (Flanagan et al., 2002) and 21g C m⁻²a⁻¹ at a semi-arid grassland, respectively (Scott et al., 2010).

Inter-annual studies of Mediterranean grassland and semi-arid chaparral, shrub ecosystems show similar implications for the variation in precipitation received during the growing season much like temperate and semi-arid systems (Luo et al., 2007; Aires et al., 2008). However, magnitudes of sequestered CO₂ recorded during years of normal precipitation were higher than the values observed at the temperate and semi-arid grasslands. A Mediterranean grassland sequestered 190 g C m⁻²a⁻¹ under normal weather conditions (Aires et al., 2008) and a chaparral shrub ecosystem in Southern California sequestered 155 g C m⁻²a⁻¹ (Luo et al., 2007). Similar to temperate and semi-arid grasslands, both ecosystems became a CO₂ source under drought conditions; the Mediterranean grassland a moderate source of 49 g C m⁻²a⁻¹ (Aires et al., 2008) and the chaparral shrub ecosystem a strong source of 207 g C m⁻²a⁻¹ (Luo et al., 2007). The large differences in annual Net Ecosystem Exchange (NEE) reported for a dry and average

precipitation year confirms the same sensitivity to precipitation as temperate and semi-arid grassland ecosystems.

The dominant influence on the carbon sink/source status and their corresponding magnitudes of NEE of Mediterranean ecosystems is not only the amount of precipitation received but also the timing when precipitation is received (Xu and Baldocchi, 2004; Luo et al., 2007; Aires et al., 2008). During years with equivalent amounts of precipitation received, integrated values of GPP, RE, and NEE were impacted by the timing of the rain at a Mediterranean annual grassland in California (Xu and Baldocchi, 2003). Because the rain was received later in the year than normal for this ecosystem, vegetation started to grow later and resulted in a shorter growing season. This produced lower values of GPP ($729 \text{ g C m}^{-2}\text{a}^{-1}$), RE ($758 \text{ g C m}^{-2}\text{a}^{-1}$), and NEE ($29 \text{ g C m}^{-2}\text{a}^{-1}$), compared to the longer growing season magnitudes of GPP ($867 \text{ g C m}^{-2}\text{a}^{-1}$), RE ($735 \text{ g m}^{-2}\text{a}^{-1}$), and NEE ($-132 \text{ g C m}^{-2}\text{a}^{-1}$) recorded (Xu and Baldocchi, 2004). The increase in GPP was responsible for turning the ecosystem into a CO_2 sink during the longer growing season in combination with lower RE values than during the shorter growing season. The occurrence of rain events during the dry season may have influenced this outcome (Xu and Baldocchi, 2004).

Large respiration pulses can occur when dried out soils receive unseasonal precipitation in Mediterranean grassland ecosystems. The water quickly stimulates

microbial activity, resulting in high CO₂ production. Xu and Baldocchi (2004) observed large respiration spikes at a Mediterranean annual grassland site in California; the net ecosystem exchange was negatively affected by the high RE (94 g C m⁻²), changing the ecosystem from a CO₂ sink to a CO₂ source during a year with a delayed rainy season (Xu and Baldocchi, 2004).

1.6 Research Objective

A vast amount of literature exists that documents the carbon dioxide exchange of natural ecosystems and research pertaining to urban ecosystems is slowly growing. A small number of studies have been conducted trying to quantify the carbon dioxide exchange of smaller ecosystems within the urban environment such as parks, but the net ecosystem exchange of living roofs is largely unknown to date. As urban areas further expand changing land use in its course, it becomes increasingly important to explore effective ways to integrate vegetation in urban planning for anthropogenic CO₂ mitigation. Living roofs have the potential to aid in offsetting urban CO₂ emissions and provide a good alternative to increase the vegetation fraction in a city without utilizing expensive real estate space.

This is the first study published that employs the eddy covariance EC method to obtain measurements of the carbon dioxide exchange between a living roof and the atmosphere over a long-term period. Results from this study on the living roof of the

California Academy of Sciences (CAS) in San Francisco will add to the understanding of how a living roof ecosystem functions and whether it is a CO₂ sink or source on an annual basis. The evaluation of the temporal variations of the Net Ecosystem Exchange (NEE) and its components, Gross Primary Production (GPP) and Respiration (RE), will further yield important data to analyze ecosystem behavior. The main objective of this study is to:

- Quantify diurnal, seasonal, and annual exchanges of carbon dioxide between an extensive living roof and the atmosphere from July 2014 to June 2015.
- Estimate partitioning of the net CO₂ flux into living roof ecosystem photosynthesis (gross primary production) and respiration components and examine environmental controls on their functioning.
- Compare these findings to similar natural Mediterranean grassland/chaparral and urban ecosystems.

Findings from this study will contribute to the knowledge base of CO₂ emission and uptake processes as well as the controls influencing such processes on living roofs in urban areas. The data can be used to provide guidance to urban planners pertaining to sustainable growth and emission offset strategies.

2.0 METHODS

2.1 Study Site

The study was conducted over a period of one year, from July 1, 2014 to June 30, 2015, in San Francisco, CA, U.S.A. San Francisco is subject to a Mediterranean climate with average maximum and minimum summer temperature variations between 10 C° and 20 C° (Null, 1991). Precipitation is mainly (~95%) received during November through March, averaging ~600 mm per year (Null, 1991). Even though San Francisco experienced a drought with less than 200 mm rain per year during the study period, the living roof did not experience the full impact of the drought due to regular irrigation at night. The study site is exposed to cool, persistent fog and westerly winds in summertime due to its close proximity to the Pacific Ocean (Null, 1991).

The research site was located on the roof of the California Academy of Sciences (CAS) museum in the eastern part of Golden Gate Park in San Francisco, California, (37.77°N, 122.48°W) approximately 4 km from the Pacific coast (Figure 3 (a) and (b)). Golden Gate Park is a mixed-use urban park with an approximate size of 412 ha (SF Parks and Rec., 2014). It is bordered by neighborhoods and on the western end by the Pacific

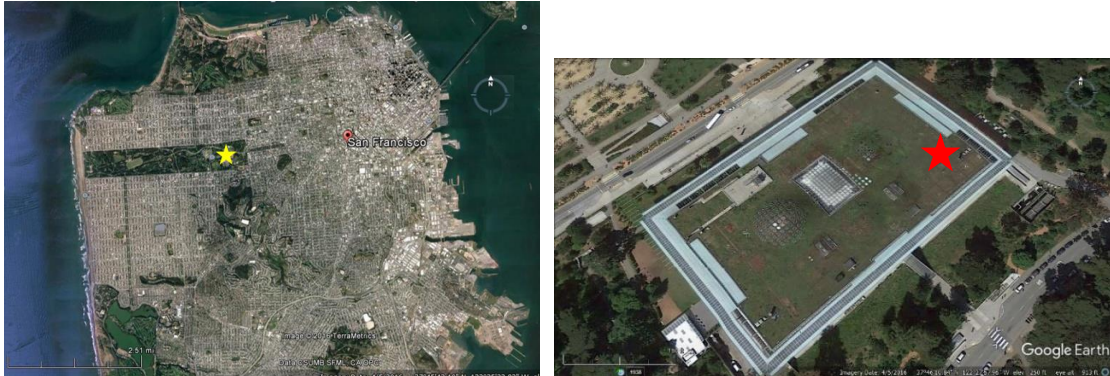


Figure 3. Google Earth images of the study site including (a) San Francisco, CA, with location of California Academy of Sciences (CAS) in Golden Gate Park marked with a yellow star and (b) California Academy of Sciences roof with location of micrometeorological station indicated with a red star.

Ocean. The building is surrounded by trees and grass areas as well as roads that wind through the park, connecting a few larger buildings close by. The CAS houses a planetarium, an aquarium, a natural history museum, and a tropical rain forest that expands four-stories from the basement to the dome. The dome is one component of the living roof that covers the CAS building. Other major components of the roof features are living vegetation, a small concrete observation deck, a glass atrium, and skylights. There are a number of vents present and the topography includes three vegetated domes 3-5 m tall, and four smaller ones positioned around the atrium (Figure 4). The substrate of the living roof has an approximate depth of 15 cm, classifying it as an extensive (shallow substrate ~ up to 150 mm) rather than an intensive roof (substrate layer larger than 150 mm) (Kolb and Schwarz, 1999). However, since the roof has an irrigation system and a small portion is accessible to the public, two attributes of an intensive living roof, it may be categorized as a combination of both.



Figure 4. California Academy of Sciences (CAS) in San Francisco, CA, showing roof topography with features consisting of domes, a glass atrium, and observation deck. The red star indicates approximate position where the flux tower was installed during the study period. Photo: Steve Proehl.

The CAS living roof was designed by architect Renzo Piano in 2008 and encompasses a surface area of approximately 10,241 m² (Cal Academy, 2014). Originally, the roof was planted with approximately 1.7 million plants of coastal California native ecosystems: coastal scrub and north coastal prairie communities of herbs, shrubs and grasses – but predominately grass and wildflower species. Additional natives and non-natives have colonized the roof since then, although non-natives are weeded out on a weekly basis. Lavender (2015) conducted vegetation surveys in spring 2014, using a similar sampling technique to that of Kalra (1996). The dominant species found by surface cover were the *Fragaria chiloensis*, *Achillea millefolium*, *Lupinus spp*, and *Festuca spp* (Table 1).

Table 1. List of plant species found on the living roof of the California Academy of Sciences in San Francisco surveyed in 2014 (Lavender, 2015) with their respective percentage of cover area and classified plant community.

Plant Species	Latin Name	% Cover Area	Plant Community
Beach strawberry	<i>Fragaria chiloensis</i>	32.9	Northern Coastal Scrub
California bent grass	<i>Agrostis densiflora</i>	11.8	Northern Coastal Scrub, Grassland
Bare soil	N/A	8.8	N/A
Foxtail fescue	<i>Festuca</i>	7.0	Chaparral
Common yarrow	<i>Achillea millefolium</i>	5.6	Coastal Prairie, Chaparral, Grassland
Fireweed	<i>Chamerion angustifolium</i>	3.4	Grassland

The average canopy height measured in May 2014 was 14.6 cm with a foliar cover of approximately 90% (Lavender, 2015). See Appendix A for a comprehensive list of all species with their respective percentage cover area identified by Lavender, 2015. The CAS living roof is maintained by weeding, to remove non-native species, and by irrigating regularly during dry months to retain a pleasing ecosystem appearance for museum visitors (Cal Academy, 2014). The soil mix is lightweight and porous, classified as sandy clay soil based on visual observations by Thorp (2014), and is further described by Cal Academy (2014) as soil that best sustains the California native plant species. It contains coconut husk and is supplemented with compost (Cal Academy, 2014).

2.2 Instrumentation and Eddy Covariance Method

Micrometeorological instruments mounted on a tripod tower included an Infrared gas analyzer (Li7500A LiCOR Instruments, Lincoln, NE) to measure CO₂ concentrations, and a 3D sonic anemometer (CSAT3, Campbell Scientific, Logan, UT) to measure vertical wind velocity, both installed 1.04 m above ground level. Additional equipment used were air temperature and humidity measurements (HMP45c, Vaisala, Helsinki, Finland), 1.09 m above ground, a four component radiometer (NR01, Hukseflux, Delft, The Netherlands) measuring solar and long-wave radiation 1.24 m above ground, and a quantum sensor to measure photosynthetically-active radiation (PAR) and diffuse PAR (BF5, Delta-T, Cambridge, UK) 1.32 m above ground. Soil temperature measurements were obtained with soil thermistors (CS107, Campbell Scientific, Logan, UT) at a depth of 3 cm, 5 cm, and 15 cm. Volumetric water content of the soil was obtained from a time-domain reflectometer (CS616, Campbell Scientific Inc., Logan, UT) from the surface down to 14 cm. A TE525 rain gauge (Campbell Scientific, Logan Utah), measuring precipitation and irrigation, was deployed at 0.4 m. The instruments were powered by multiple 12 V deep cycle batteries charged by a 75 W solar panel (later supplemented by AC power from the building). The eddy covariance flux station was installed on the southeastern (leeward) corner of the roof (Figure 3 (b)). This location was chosen because it allowed for the longest fetch on the roof with up to 140 m in the prevailing westerly wind

direction (Figure 5 (a)). All data were collected and stored in a CR3000 data logger; measurements were taken 10 times per second and averaged into 30-minute periods.

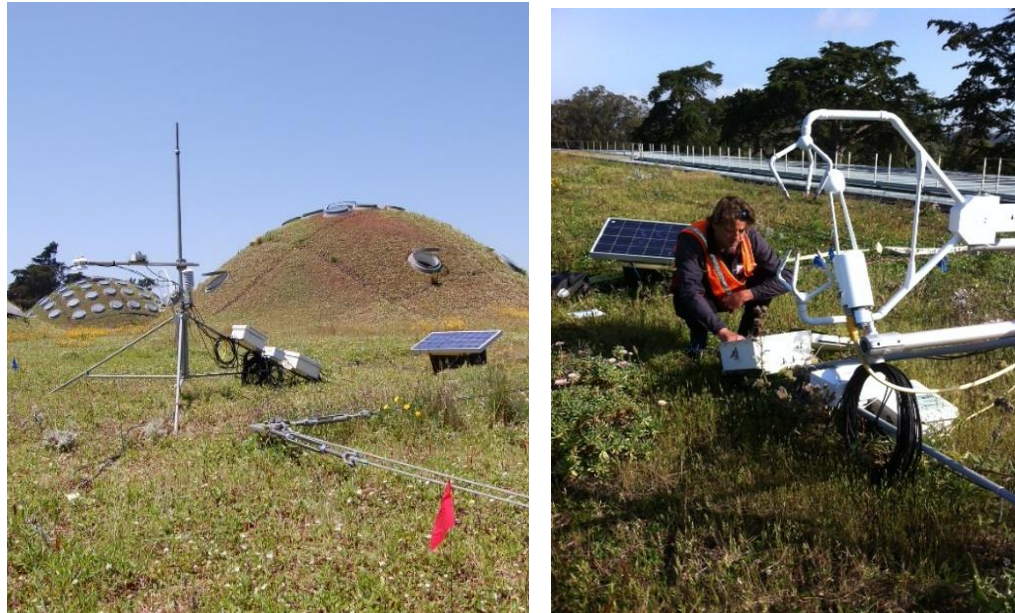


Figure 5. The eddy covariance flux station on the California Academy of Sciences roof: (a) showing the view facing west, in the prevailing westerly wind direction, and (b) researcher checking data logger to ensure accurate functioning of instruments.

This study utilized the eddy covariance (EC) technique to determine surface-atmosphere exchanges of carbon dioxide. The eddy covariance technique measures fluxes, or the rate of flow of atmospheric scalars by simultaneously sampling vertical wind velocities driven by turbulent motions (eddies) and the scalar of interest (Baldocchi 2003; Oke 1987). Due to the turbulence, all atmospheric entities near the surface show short-term fluctuations over their longer term mean (Oke 1987). Based on this concept, the equation for eddy covariance is expressed:

$$F_{CO_2} = \rho \overline{w'co_2'} \quad (1)$$

where F_{CO_2} , the measured fluxes, are equal to the air density (ρ) multiplied by the time average of the instantaneous covariance of vertical velocity (w') and the concentration of carbon dioxide (CO_2') (Baldocchi 2003; Burba et al. 2011; Oke 1987). The overbar indicates the mean of the instantaneous covariance, or degree to which the vertical velocity and the CO_2 vary over the selected time average (Burba et al. 2011). The prime denotes the instantaneous deviation from the longer term mean (Burba et al. 2011). By micrometeorological convention, positive fluxes towards the atmosphere indicate a net emission and negative fluxes towards the surface, a net uptake (Crawford et al., 2011).

The eddy covariance technique (EC) is the only existing method that can directly measure CO_2 fluxes that incorporate all natural and anthropogenic sinks and sources (Velasco and Roth, 2010). Other benefits include the capability to capture precise, high-frequency measurements. This technology has been widely utilized for grassland, wetland, and forest ecosystems (Baldocchi, 2003), but the datasets of meaningful measurements for the much more challenging urban environments are small. Its application is rather complex and careful attention is required for the selection of the measurement site (Velasco and Roth, 2010). Equipment must be placed approximately two and a half times the mean surface height above the measured surface area to

capture F_{CO_2} from the desired sources. Both the positioning of instruments and the data processing in order to collect meaningful and representative results are crucial (Velasco and Roth, 2010).

2.3 CAS Flux Footprint

The footprint, also called source area or fetch, reflects the fraction of the surface area that contains the sinks and sources contributing to the vertical flux measured at the flux tower (Baldocchi, 2003; Velasco and Roth, 2010). The flux tower height, combined with the surface roughness length, the intensity of the turbulence, the wind speed and direction, and the thermal stability of the atmosphere determine the flux footprint (Velasco and Roth, 2010). Drawbacks of the eddy covariance technique include that the study site must be relatively flat and of homogenous terrain to be measured accurately. This represented a particular challenge for the CAS study site because of the relatively small and complex roof area. In general, a footprint extending between 100 and 300 times the actual measurement height is used as an estimation for the source area of the flux measurements (Velasco and Roth, 2010). The eddy covariance instruments were installed as low as possible to the surface on the CAS roof (approximately 1m above ground), resulting in an average 80%ile fetch distance (Thorp, 2014). A flux source area model was calculated for every 30-minute interval, based on Hsieh et al.'s (2000)

analytical model. The resulting data was used to reject all periods when the 80th percentile of the cumulative flux distance fell outside of the roof area.

To be able to use EC, the surface must be homogeneous so that advection can be discounted (Wofsy et al. 1993; Moncrieff et al. 1997), but, as previously mentioned, the CAS roof is rather complex. Even though the vegetation height across the roof is relatively homogenous, there are a number of multi-meter domes present, which could affect local area flux deviations. According to Thorp (2014), the instruments were placed in such a way that the dominant wind came through in between the domes, achieving a mostly flat surface area for the flux footprint. The micrometeorological equipment was installed about 15 m away from the building edge to reduce possible influences of vertical wind motions (Lavender, 2015).

2.4 Data Rejection, Restrictions, and Uncertainties

The data collected from July 2014 to June 2015 was imported into MatLab for analysis. The following data quality control criteria were employed:

1. Stable atmospheric conditions during the night lead to low friction velocity (u^*) - data with a less than 0.15 m s^{-1} u^* were rejected due to insufficiently developed turbulence for measurement.
2. As described in section 2.3 (CAS Flux Footprint), the flux source area (footprint) was estimated for every 30-minute period using the Hsieh et al. (2000) analytical footprint

- model – following commonly used rejection criteria (Velasco et al. 2005), all periods were rejected when the 80th percentile of the cumulative flux distance fell outside of the roof area.
3. Any CO₂ flux measurements exceeding 0.6 g C m⁻²s⁻¹ / -0.6 g C m⁻²s⁻¹, respectively, were rejected to remove physically unreasonable values and large implausible spikes from the data.

These restrictions resulted in large data rejections. Considerably more of the accepted data were collected during daylight periods than night periods, mainly due to stable atmospheric conditions during the night. In order to reduce the daytime bias in the data, monthly diurnal averages were generated based on ensemble averages of each of the 48 30-minute periods. For monthly and seasonal averages, gap-filling was needed to derive data points (mostly in winter and at night). For this purposes environmental drivers were used to develop empirical models.

The roof ecosystem also included a glass atrium roof (~625 m²), a concrete viewing deck (~275 m²), and numerous ventilation windows embedded within the domes (Thorp, 2014). Due to these features, it is assumed that CO₂ measured may include carbon sources other than heterotrophic and autotrophic respiration from the roof vegetation. The building structure includes environmental controls that regulate carbon dioxide concentrations inside the building; vents open automatically once 1000 ppm are

reached (Cal Academy 2014). The atrium is designed as an interior cooling feature and is usually opened at night for cool air to enter the museum (Cal Academy, 2014), at which time, also CO₂ exchange occurs between the building below and the roof. The EC method cannot distinguish between biogenic and anthropogenic sources. This leads to the assumption that the turbulent fluxes of CO₂ measured on the CAS living roof do include non-biological sources, and therefore, magnitudes of respiration (RE) may be overestimated while ecosystem sequestration is underestimated.

2.5 CO₂ Flux Partitioning and Gap Filling

Data gaps due to instrument maintenance and malfunctioning or rigorous rejection criteria, as discussed in the previous section, are unavoidable in long-term eddy covariance (EC) records. To meet the challenges of data continuity for long-term EC measurements and to be able to obtain information on monthly, seasonal, and annual totals of the carbon dioxide fluxes, environmental drivers were used to develop empirical models for gap-filling.

F_{CO2} measured by eddy covariance also estimated the net ecosystem exchange (NEE) on the living roof as it reflects the balance of CO₂ sequestered through photosynthesis (gross primary production) and CO₂ released through respiration by the ecosystem. NEE was partitioned into respiration (RE) and gross primary production (GPP) applying common methods used for natural ecosystems (Xu and Baldocchi, 2004). There

is no process for CO₂ uptake during nighttime when photosynthesis is inactive.

Therefore, nocturnal F_{CO2} were assumed to be solely due to biogenic respiration (RE) of the living roof ecosystem; NEE_{night} = RE_{night}. Past research indicates that soil respiration is strongly dependent on both soil temperature and soil moisture (Crawford et al., 2011). Since this study site was well irrigated and only changed little during the study period, it was assumed that respiration was mainly driven by soil temperature. Previous studies found exponential empirical relations between measured nighttime CO₂ fluxes and soil temperature using EC in forest ecosystems (Schmid et al., 2000; Crawford et al., 2011). A linear model was derived by using the relationship between RE_{night} from periods of high turbulence with friction velocity higher than 0.15 m s⁻¹ and the soil temperature measured at 5 cm depth:

$$RE = 0.012004 * Ts + 0.039692 \quad (2)$$

Combined data was used to estimate respiration of the living roof by including observed values when meeting rejection criteria and modeled values when not. GPP was then calculated from the newly obtained linear RE model as a residual based on the formula (Barr et al., 2002; Flanagan et al., 2002):

$$GPP = NEE - RE \quad (3)$$

Light use efficiency (LUE), the ratio of PAR to absorbed GPP, is approximately constant with respect to changes in PAR, which implies that GPP can be modeled by using

a linear relationship with PAR. Strong correlations between PAR and F_{CO_2} have been found in natural ecosystems throughout the summer growing season (Schmid et al., 2000; Xu and Baldocchi, 2004). A light use efficiency (LUE) model of GPP was created (Figure 6) based on a standard rectangular hyperbola light use efficiency function (Wofsy et al., 1999):

$$GPP = \frac{\alpha \times A_{max} \times PAR}{A_{max} + \alpha \times PAR} \quad (4)$$

where α = the initial slope of the LUE curve, A_{max} = point of maximum carbon assimilation, and PAR = incident photosynthetically active radiation. PAR data prior to day of year (DOY) 130 and after DOY 330 were rejected due to known bad data from instrument failure and gap-filled using solar radiation and the relation derived between PAR and solar radiation from periods when both datasets were present.

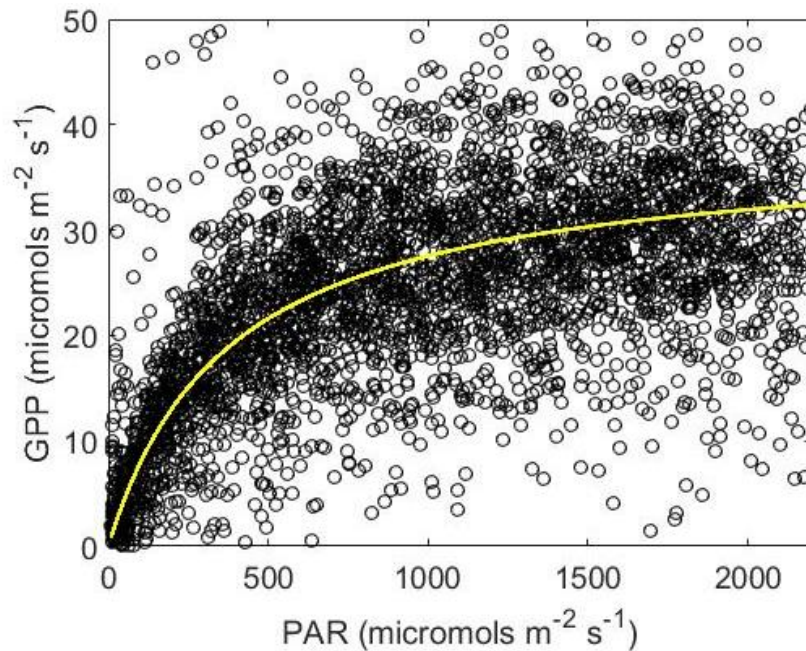


Figure 6. Light Use Efficiency (LUE) curve, showing the relationship between Photosynthetically Active Radiation (PAR) and Gross Primary Production (GPP) on the California Academy of Sciences living roof over the entire study period.

To evaluate the degree of accuracy of the newly derived models, modeled NEE was compared to observed NEE. First modeled GPP and RE values were combined to generate modeled NEE: $NEE_{\text{modeled}} = RE_{\text{modeled}} - GPP_{\text{modeled}}$. Then NEE_{modeled} was plotted to NEE_{observed} for all available 30-minute periods (Figure 7). The comparison yielded a slope of 73.2% indicating that modeled NEE underestimated the observed net ecosystem exchange by approximately 27%. This finding added to the uncertainties (e.g. anthropogenic CO_2 inclusion in measurements) discussed earlier, and the speculation that the actual carbon dioxide uptake from the living roof could possibly be greater than observed. Modeled values were included in this study to support gap-filling and make analysis of monthly, seasonal, and annual totals of the carbon dioxide fluxes possible.

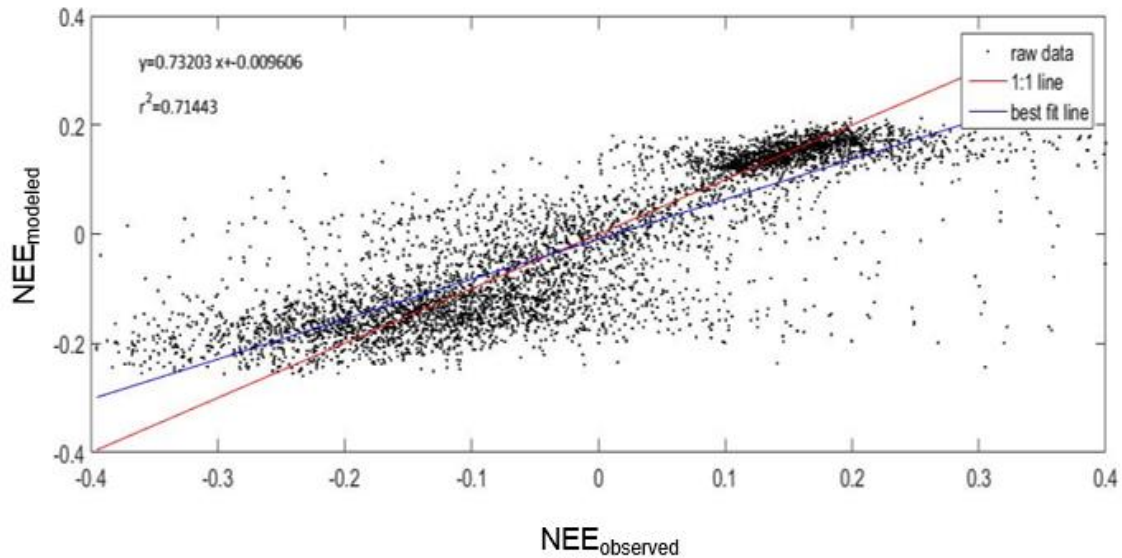


Figure 7. Comparison of observed carbon dioxide fluxes and net ecosystem exchange (NEE) with modeled NEE on the CAS living roof for all available 30-minute periods.

3. RESULTS

3.1 Net Ecosystem Exchange over CAS Living Roof

Figure 8 shows the diurnal ensembles of 30-minute averages of NEE over the entire study period. A strong diurnal signal was observed with the roof ecosystem acting as a net carbon source during the night and switching to a carbon sink shortly after sunrise. From the onset of photosynthesis, NEE dropped to reach a peak uptake rate of approximately $-0.2 \text{ mg C m}^{-2}\text{s}^{-1}$ around 10:00 PST before decreasing slowly thereafter until sunset, creating an asymmetric diurnal cycle. The night hours flux seen in Figure 8 was quite consistent throughout the night at approximately $1.8 \text{ mg C m}^{-2}\text{s}^{-1}$. The CAS

living roof was a daily net source of CO₂ (2.13 g C m⁻²d⁻¹) to the atmosphere over the course of a year. This estimate was based on considerably more data collected during spring (growth period) and summer as explained in section 2.4. Therefore, actual CO₂ magnitudes may be higher than estimated because of the seasonal bias.

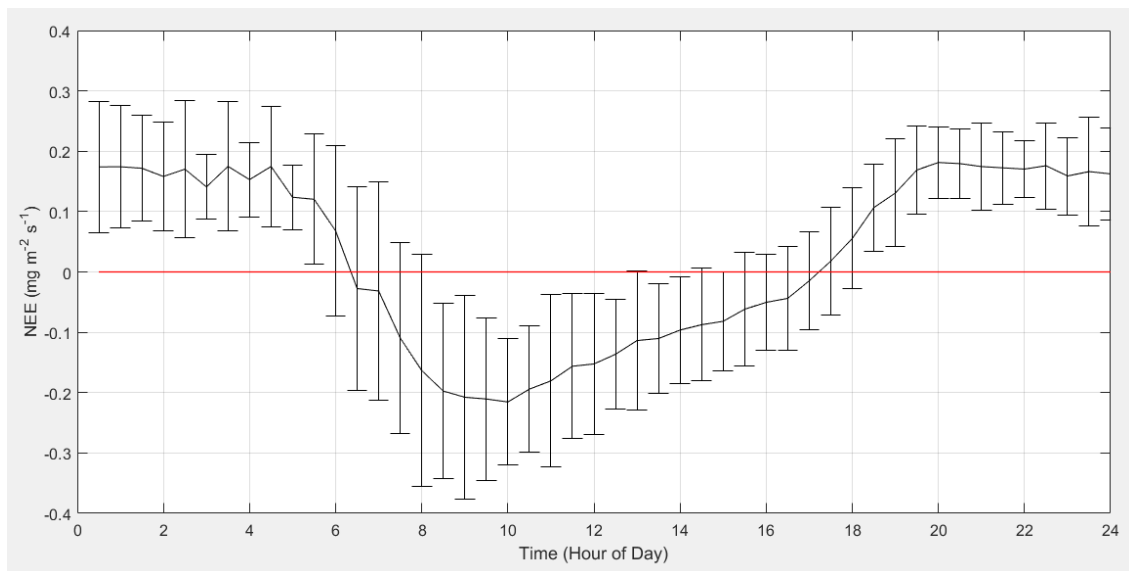


Figure 8. Diurnal ensembles of 30-minute averages of NEE over study period. Error bars represent +/- one standard deviation.

Diurnal ensembles of 30-minute averages of NEE graphed for each month show the daily patterns changing over the course of the year (Figure 9). All months of the year resemble the asymmetric nature of the diurnal cycle evident in Figure 8. After sunrise, NEE shifted from a source to a sink during all months, peaking at about

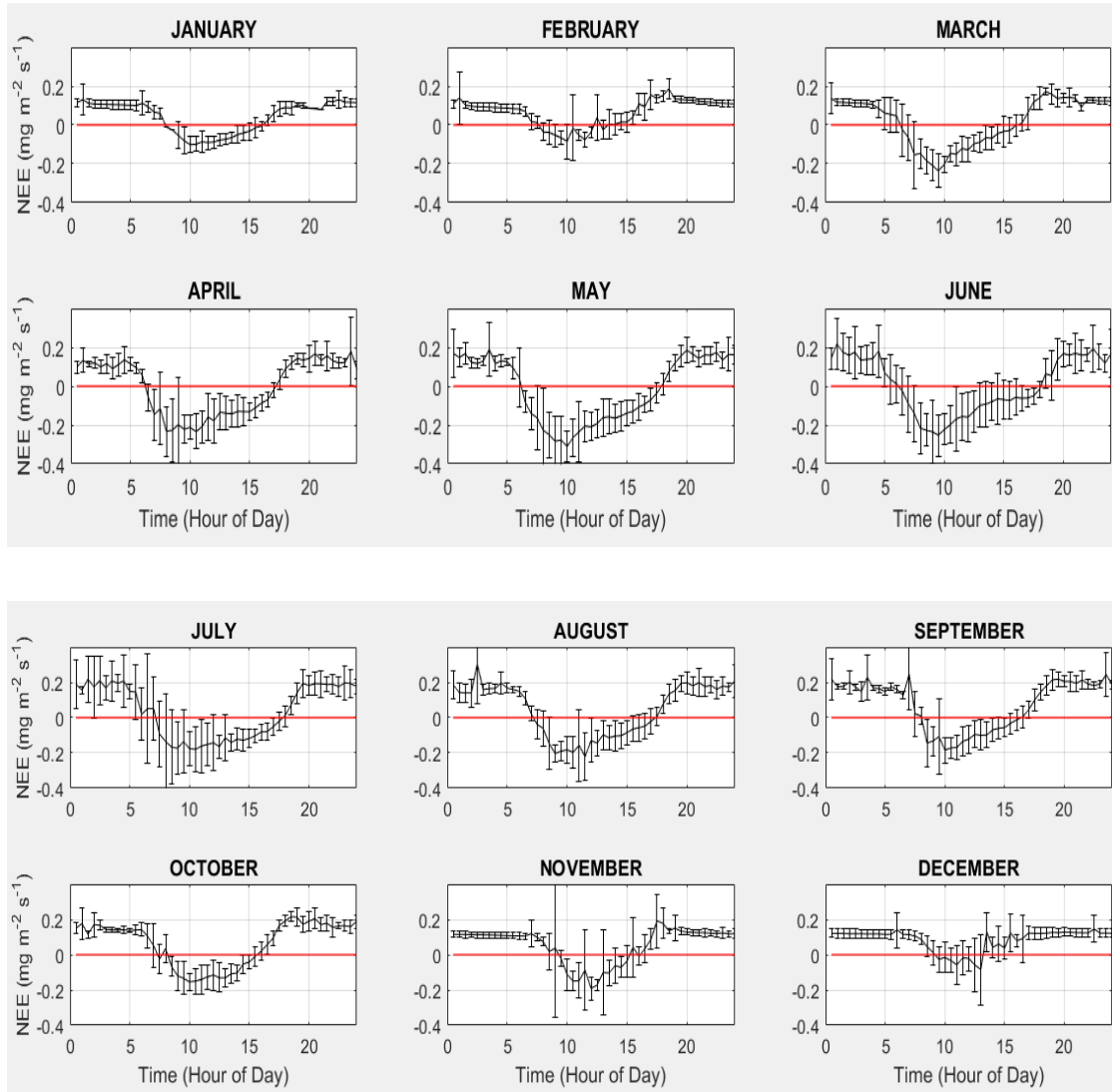


Figure 9. Diurnal ensembles of 30-minute averages of NEE per month (year 2014/2015) observed on the CAS roof ecosystem. Error bars represent \pm one standard deviation.

10:00 PST, and then slowly decreasing until becoming a source again around sunset.

Whereas the winter months show a very weak rate of uptake during daylight hours due to low light, less foliage, and also a shorter period of time (short day length), an increase in CO_2 uptake during the day is clearly visible, beginning in March, peaking in May, and

decreasing during the dry season (Figure 9). Visual observations of seasonal variations in vegetation vitality on the CAS living roof show full bloom, increased foliage cover and canopy height, during the peak CO₂ uptake month of May (Figure 10 (c)). During August and February, a much lower canopy height was observed as well as less vegetation vitality due to leaf senescence in August and pre-growth conditions in February (Figure 10). Ecosystem respiration (RE) was fairly steady at approximately 0.1 mg C m⁻²s⁻¹ during nighttime from November through May but then increased from June through October (dry season) to ~ 0.2 mg C m⁻²s⁻¹.

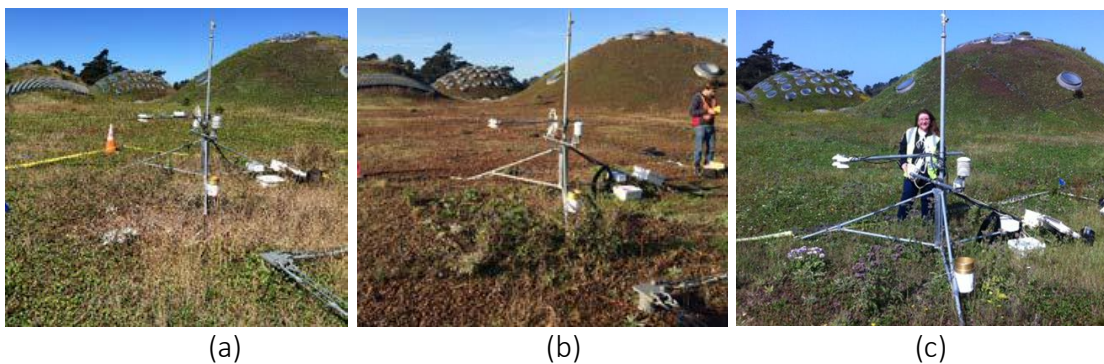


Figure 10. Seasonal variation in vegetation vitality on the California Academy of Sciences' living roof, in San Francisco CA; (a) August, 2014, (b) February 2015, (c) May 2015.

Figure 11 shows diurnal ensembles of 30-minute averages of the net ecosystem exchange (NEE) per month over the CAS living roof ecosystem. Highest daily averages were observed during winter and late summer, with December values of 7.3 g C m⁻²d⁻¹ and September 6.4 g C m⁻²d⁻¹. The monthly average daily NEE shows significant seasonal patterns, becoming a much weaker source or net sink from March to June, with monthly

values reaching $-1.3 \text{ g C m}^{-2}\text{d}^{-1}$ in May. The surface switches back to becoming a moderate source on a daily basis during the rest of the year, with an average of $4.4 \text{ g C m}^{-2}\text{d}^{-1}$. Over the entire study period from July 2014, to June 2015, the living roof was a net source of carbon dioxide of the magnitude $\sim 1,235 \text{ g C m}^{-2}\text{a}^{-1}$.

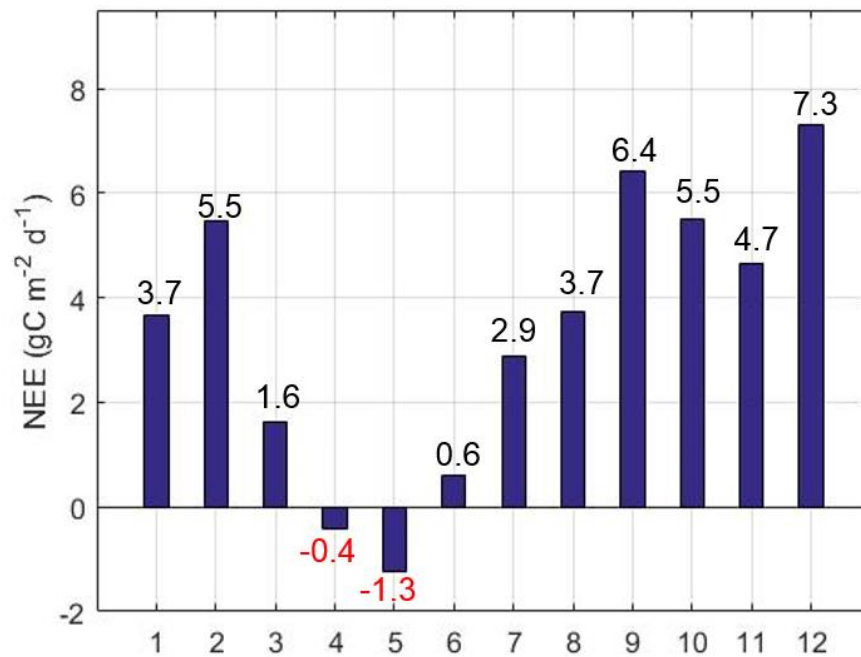


Figure 11. Diurnal ensembles of 30-minute averages of Net Ecosystem Exchange (NEE) per month (July 2014 – June 2015) over CAS living roof ecosystem.

3.2 Magnitudes of Gross Primary Production (GPP) and Respiration (RE)

The GPP of the CAS living roof was derived as a residual by deducting RE from NEE based on Equation (3). Over the entire study period, the daily average ecosystem values

for GPP and RE were approximately $-13.24 \text{ g C m}^{-2}\text{d}^{-1}$ and $13.21 \text{ g C m}^{-2}\text{d}^{-1}$, respectively. RE values included modeled data as well as actual observed data when it did not exceed rejection criteria. NEE measured was $2.13 \text{ g C m}^{-2}\text{d}^{-1}$ when averaged over the total study period. As with natural ecosystems, these magnitudes illustrated that the relatively small NEE is the result of the two larger fluxes of opposing sign. The observed NEE over the living roof did not resemble the balance between GPP and RE exactly. Based on the model accuracy analysis presented in section 2.5, the modeled RE and GPP may be underestimating F_{CO_2} by as much as 27%.

As seen in Figure 12, diurnal ensemble averages for the entire study period show CO_2 uptake (GPP) began at sunrise, increasing steadily to reach a diurnal maximum in a negative direction of approximately $-0.4 \text{ mg C m}^{-2}\text{s}^{-1}$ at around 10:00 PST, and then slowly declining until sun set. The red line in Figure 13 shows respiration as a function of ground temperature combined with observed values, staying relatively constant between 0.1 and $0.2 \text{ mg C m}^{-2}\text{s}^{-1}$ over a 24-hour period.

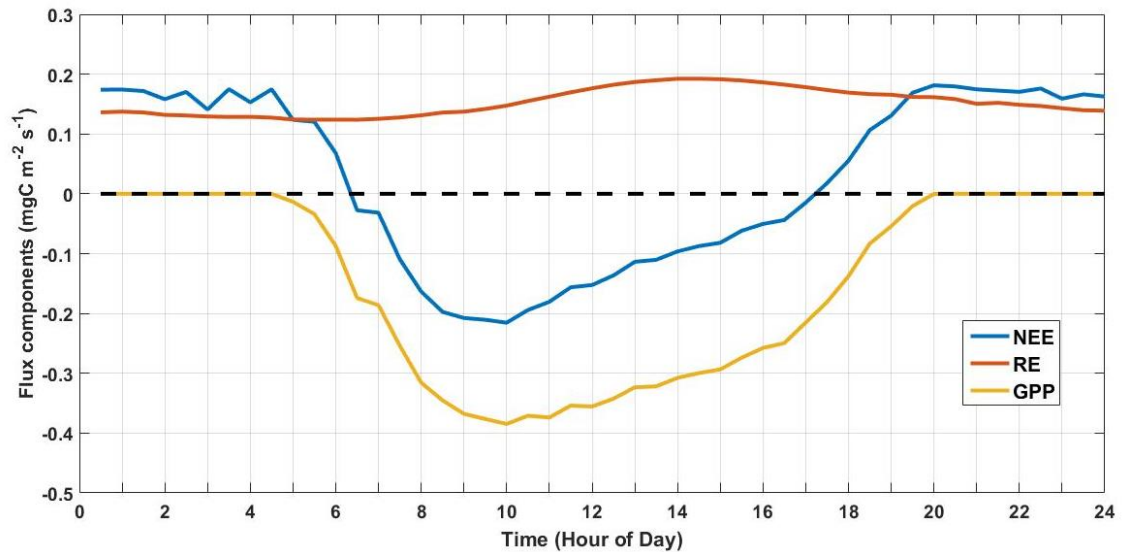


Figure 12. Diurnal ensembles of 30-minute averages of carbon flux components: Net Ecosystem Exchange (NEE) Gross Primary Production (GPP) and Respiration (RE) over entire study period, July 2014–June 2015.

3.3 Ecosystem CO₂ Exchange for Mediterranean Biome Seasons

A common seasonal breakdown used to describe Mediterranean chaparral, shrub, and grassland ecosystems, is the pre-growth, growth, and dry period (Xu and Baldocchi, 2003; Luo et al., 2007; Aires et al., 2008). The pre-growth period in Mediterranean ecosystems begins somewhere around October, depending on when the first major rain event is received (above 15 mm of precipitation) and lasts until March. The grass phenology closely follows soil moisture because of the shallow root system, and grass seed germination usually occurs in fall, one week after a major rain event (Xu and Baldocchi, 2004). During the pre-growth period, plant growth occurs but leaves are still

immature and don't photosynthesize to the extent the mature plants will later in spring. The combination of warmer temperatures, ample soil moisture, and longer day length in spring enhances grass growth (Xu and Baldocchi, 2004), which reaches normally a peak Leaf Area Index during that time. In Mediterranean grassland ecosystems, the growth period may begin during the month of March and may last until late June. The growth period does not last long, however, because the rainy season ends approximately in April. Soon thereafter, the plants will have utilized much of the soil moisture, leading to grass senescence, which defines the dry season. The dry period lasts from the beginning of leaf senescence (normally from late June to October) until the first rain is received in fall again. The grass seeds will lie dormant during the dry and warm summer.

A common method used to define the growth period is by determining the Leaf Area Index (LAI) (Xu and Baldocchi, 2004; Aires et al., 2007). Grass is harvested at 2-4 weeks intervals, leaves are separated from the stem, and their areas measured with a leaf area meter. LAI increases towards the peak growing season and can be twice as large as during the pre-growth period.

To better understand the seasonal differences in the ecosystem CO₂ exchange over the CAS living roof, the year was divided into three main periods of growth, similar to those defined by Xu and Baldocchi (2004). Pre-growth was defined as the period between 1 October and 31 March, based on the normally occurring rain season for Mediterranean ecosystems. The growth period was defined as the period between 1

April and 15 June. This study did not include the LAI method but estimated the growth period based on observed diurnal ensembles of 30-minute averages of NEE over the twelve month period (Figure 11) and on visual observations (Figure 10). The remaining period until 30 September was defined as dry.

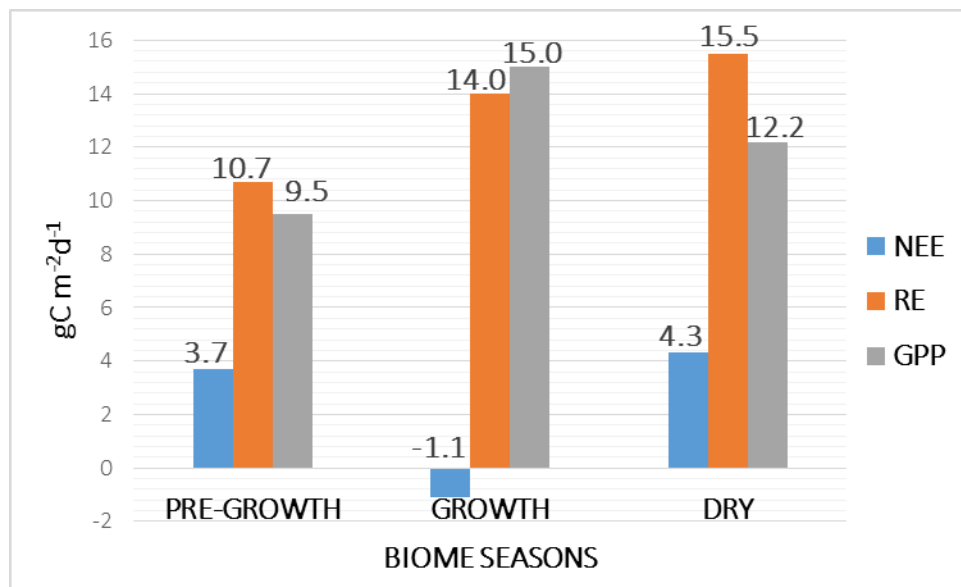


Figure 13. Mean daily CO₂ exchange, Net ecosystem exchange (NEE), Respiration (RE), and Gross Primary Production (GPP) for the Pre-growth, Growth, and Dry periods of CAS roof during July 2014-June 2015.

A close inspection of Figure 13 evidences that the roof ecosystem was a diurnal CO₂ sink on the magnitude of approximately -1.1 g C m⁻²d⁻¹ during the growth period. During the dry and pre-growth periods, the living roof was a large daily CO₂ source of 4.3 g C m⁻²d⁻¹ and 3.7 g C m⁻²d⁻¹, respectively. The highest respiration rates were found during the dry period at 15.5 g C m⁻²d⁻¹, likely because of the higher nocturnal respiration observed from June through October (Figure 9) due to warmer soil temperatures during

summer. Diurnal ensemble averages show the lowest carbon uptake rates (GPP) in the pre-growth period ($9.5 \text{ g C m}^{-2}\text{d}^{-1}$) possibly due to shorter day length. GPP increased to $15.0 \text{ g C m}^{-2}\text{d}^{-1}$ during the growth period and then decreased again to $12.2 \text{ g C m}^{-2}\text{d}^{-1}$ during the dry period.

Figure 14 illustrates that the roof ecosystem switches from a source to a sink after sunrise, remaining a CO_2 sink during the daylight hours for all three biome seasons. Maximum F_{CO_2} reached during the growth period were $-0.25 \text{ mg C m}^{-2}\text{s}^{-1}$, during the dry period $-0.18 \text{ mg C m}^{-2}\text{s}^{-1}$, and $-0.22 \text{ mg C m}^{-2}\text{s}^{-1}$ during the pre-growth period. For all three periods, the living roof acted as a CO_2 source in the evening, through the night and into the early morning hours. Nighttime respiration was lowest during the pre-growth period, averaging at around $0.1 \text{ mg C m}^{-2}\text{s}^{-1}$, due to cooler temperatures, but increased to $0.15 \text{ mg C m}^{-2}\text{s}^{-1}$ during the growth period and was highest at about $0.2 \text{ mg C m}^{-2}\text{s}^{-1}$ during the dry period (Figure 14). Again, the same asymmetry of the diurnal cycle found earlier is evident in all biome seasons.

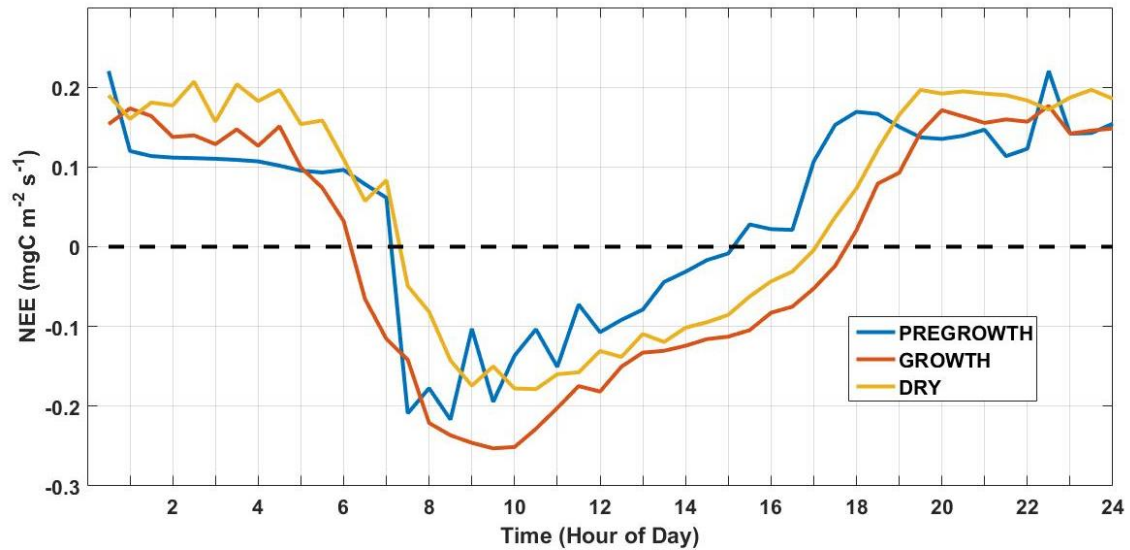


Figure 14. Diurnal ensembles of 30-minute averages of Net Ecosystem Exchange (NEE) during three biome seasons; growth, pre-growth, and dry periods.

3.4 Environmental Controls on Respiration and Gross Primary Production

As discussed in section 2.5, for most ecosystems, nocturnal net F_{CO_2} can be assumed to equal nighttime respiration because photosynthesis processes that sequester CO_2 during daylight are inactive at night (Xu and Baldocchi, 2004; Crawford et al., 2011). Furthermore, combined autotrophic and heterotrophic respiration of an ecosystem has been found to vary most strongly with soil temperature as well as soil moisture (Schmid, 2000; Flanagan et al., 2002; Crawford et al., 2011). However, when a site is well irrigated and soil moisture only changes little over time, soil temperature can be assumed to be the main factor (Crawford et al., 2011). The relationship between the nocturnal F_{CO_2} (respiration) and the soil temperature is presented in Figure 15. In this study, the

relationship between soil temperature and nocturnal F_{CO_2} was positive and linear. The binned averages of 1°C increments show a strong biological relationship ($R^2 = 0.96$) but

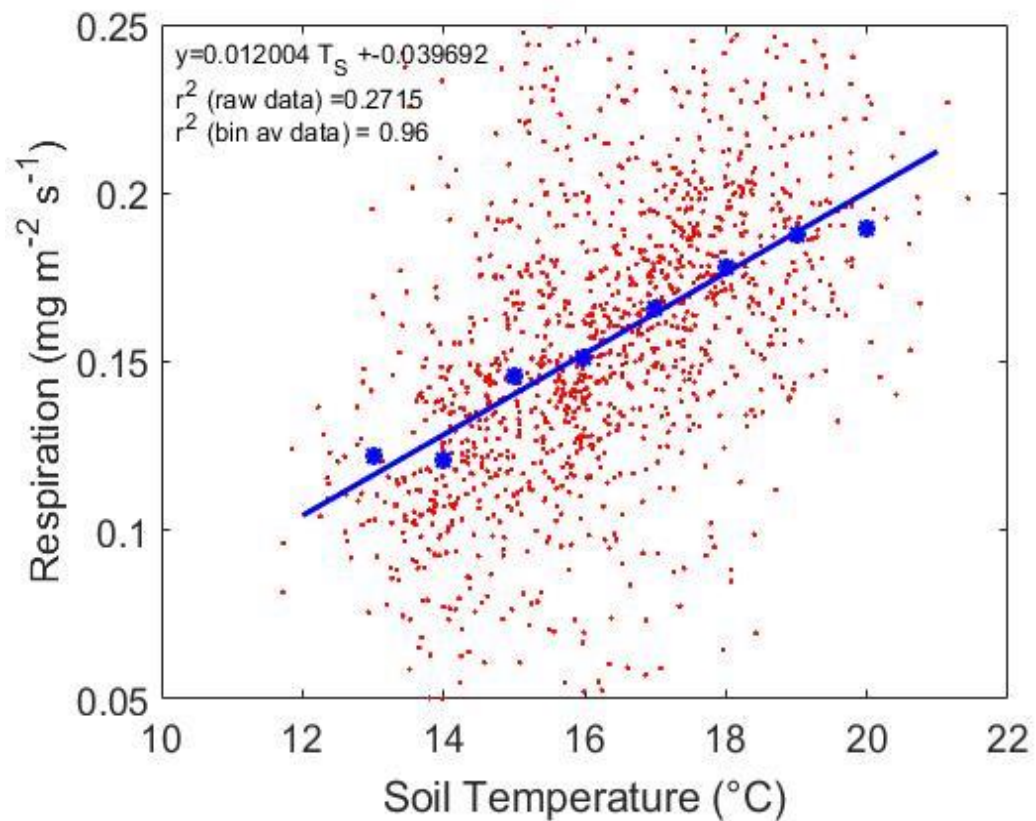


Figure 15. Soil temperature as a predictor of nocturnal respiration on the CAS living roof. Binned averages of temperature in 1°C increments.

the smaller red dots, reflecting the 30 minute periods, show a much larger amount of scatter ($R^2 = 0.27$). This implies that some of the individual 30-minute periods could include other CO_2 sources than the living roof ecosystem, for example, when building

ventilation was opened during certain times. Therefore, other factors may influence respiration rates beyond the biological functioning of the living roof ecosystem.

Vegetation photosynthesis is the only process sequestering CO₂ from the atmosphere during daylight hours in the growing season (Crawford et al., 2011). This process is primarily controlled by the vegetation's access to photosynthetically active radiation (PAR). Since the structure and function of the living roof ecosystem was found to change over the year in three distinct seasons, the light use efficiency (LUE) was examined over the previously determined growing periods. A rectangular hyperbolic function after Wofsy et al. (1999), equation (4), was used to describe the relationship between PAR and gross primary production (GPP) of the living roof. Figure 16 illustrates the response of daytime GPP to incident PAR. All three LUE curves show that PAR is strongly correlated with GPP with initial steep slopes and with photosynthetic activity increasing as PAR levels increase. Towards the point of maximum carbon assimilation, the rate of CO₂ uptake slows, implying a canopy light saturation effect (Chalker, 1980; Crawford et al., 2011). This indicates that the living roof functions very similar to natural ecosystems.

The growth curve shows the steepest initial slope ($\alpha = 0.11$) out of the three periods, indicating the highest light use efficiency (LUE). During the dry period the slope value observed was $\alpha = 0.10$ and $\alpha = 0.06$ during the pre-growth period. The low α

during the pre-growth period may be due to a much lower vegetation cover and low temperatures. The point of maximum carbon dioxide assimilation (A_{\max}) was $40 \mu\text{mol m}^{-2}\text{s}^{-1}$ during the growth period (Figure 16). The dry period showed a very similar response with an A_{\max} of $35 \mu\text{mol m}^{-2}\text{s}^{-1}$ not quite reaching the GPP magnitudes of the growth period, which may be attributable to leaf senescence and higher temperatures, causing partial stomatal closure. The lowest A_{\max} $20 \mu\text{mol m}^{-2}\text{s}^{-1}$ was found during the pre-growth period, most likely due to the smallest canopy size and low temperatures. In comparison, very similar results were reported for the pre-growth and growth periods, 24.6 and $40.2 \mu\text{mol m}^{-2}\text{s}^{-1}$, respectively, for a Mediterranean grassland (Xu and Baldocchi, 2004). Lower magnitudes were observed at a temperate grassland with a calculated A_{\max} of $27.5 \mu\text{mol m}^{-2}\text{s}^{-1}$ during the growing season (Flanagan et al., 2002). This indicates that the light use efficiency of the living roof ecosystem falls within natural grassland ecosystems' range.

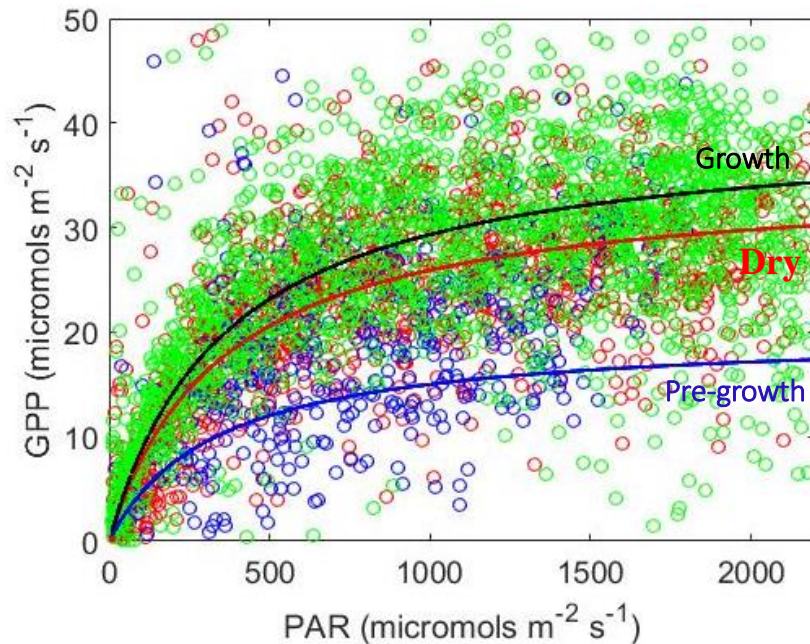


Figure 16. Light Use Efficiency (LUE) curves, showing the relationship between Photosynthetically Active Radiation (PAR) and Gross Primary Production (GPP) during growth, dry, and pre-growth periods.

4.0 DISCUSSION

4.1 Comparison of Living Roof Ecosystem to Urban Ecosystems

In terms of the CO₂ exchange, the living roof can be seen as a hybrid ecosystem, exhibiting certain behaviors of an urban and some of natural ecosystems because of its unique setting on a rooftop within an urban area. Over the total study period, the CAS living roof was a weak daily CO₂ source to the atmosphere. Magnitudes of carbon dioxide emissions measured were similar to the ones found in

suburbs with a higher fraction of vegetation. Short-term observations made at a Chicago suburb found a daily average CO_2 flux (F_{CO_2}) of $3.8 \text{ g C m}^{-2}\text{d}^{-1}$ (Grimmond et al., 2002), and the daily average long-term F_{CO_2} at a highly vegetated site in Baltimore, MD, was estimated at $0.99 \text{ g C m}^{-2}\text{d}^{-1}$ (Crawford et al, 2011). Both F_{CO_2} very closely compare to the living roof's daily average of $2.13 \text{ g C m}^{-2}\text{d}^{-1}$.

In suburban environments, Crawford et al. (2011) and Bergeron and Strachan (2011) observed significant seasonal differences in F_{CO_2} diurnal patterns due to carbon sequestration through vegetation, in studies conducted in Baltimore, MD, and Montreal, Canada, respectively. Diurnal patterns reflected that the study sites were a carbon source during winter but showed a marked daytime CO_2 uptake during the growing season comparable to the CAS living roof. The living roof also displayed similar behavior to an urban park in Essen, Germany, where it was found that the park F_{CO_2} was governed by plant activity, showing negative daytime F_{CO_2} with a mean maximum uptake of $-4 \mu\text{mol m}^{-2} \text{ s}^{-1}$ (Kordowski and Kuttler, 2010). Nocturnal F_{CO_2} remained positive because of plant/soil respiration, signaling a carbon source, as seen with the living roof ecosystem.

The living roof diurnal cycle was found to be of an asymmetric nature, looking unnatural by showing an average daily peak CO_2 uptake rate at 10:00 PST for every

month of the year and the three biome seasons. Similar patterns are sometimes observed with semi-arid and arid grassland ecosystems subject to high daytime temperatures and water stress (Valentini et al., 1995; Xu and Baldocchi, 2004). The CAS living roof was neither subject to drought conditions nor high air temperatures, therefore, it may be concluded that other sources stemming from the building below influenced this unusual pattern. The California Academy of Sciences opens the doors to the public daily at 9:30 PST, which leads to the assumption that activity associated with the museum after it opens, produces anthropogenic CO₂ emissions that were captured by the eddy covariance equipment on the living roof above.

Table 2 lists selected cities with the corresponding annual CO₂ flux. Even though the living roof was an annual source of CO₂ to the atmosphere, the estimated net annual F_{CO2} of 1,235 g C m⁻²a⁻¹ was relatively small compared to other urban sites that can reach an estimated annual F_{CO2} up to 9,673 g C m⁻²a⁻¹ as seen in London, UK (Helfter et al., 2010). Crawford et al.'s (2011) study demonstrates that urban sites with low population density and high vegetation fractions (~67%) produce a much smaller net annual CO₂ flux and can serve as a carbon sink during the summer months. Similarly, the living roof clearly sequestered CO₂ during the daylight hours and was a carbon sink during the growing period. However, it could not sequester enough carbon to turn this site into a carbon sink over the entirety of a year.

Table 2. Comparison of Living Roof to Urban Ecosystems: Net annual ($\text{g C m}^{-2}\text{a}^{-1}$) carbon dioxide flux of selected cities.

City	Net annual CO_2 flux	Source
London, UK	9673	Helfer et al. (2010)
Vancouver, CA	6710	Christen et al. (2010)
Essen, Germany	3940	Kordowski and Kuttler (2010)
Tokyo, Japan	3352	Moriwaki and Kanda (2004)
Melbourne, Australia	2313	Coutts et al. (2007)
CAS Living Roof	1235	This study
Baltimore, USA	361	Crawford et al. (2011)

4.2 Comparison of Living Roof Ecosystem to Natural Ecosystems

The living roof ecosystem exhibited in many ways biological functioning similar to natural ecosystems. It sequestered CO_2 during the daylight hours and was a CO_2 sink from sunrise to sunset during all months of the year, if just a weak one during the winter months. However, it did not absorb a large enough amount of CO_2 to compensate for or to exceed the respiration rates, driven by plant and soil respiration of the roof ecosystem as well as sources from the building beneath. Nighttime ecosystem respiration (RE) on the living roof increased from $\sim 0.1 \text{ mg C m}^{-2}\text{s}^{-1}$ to $\sim 0.2 \text{ mg C m}^{-2}\text{s}^{-1}$ in June through October (dry season). High nocturnal F_{CO_2} can occur due to warmer soil temperatures during the summer months. Also, Xu and Baldocchi (2004) found that unseasonal rainfall or in this case supplemental irrigation

during the dry season, may cause respiration spikes as observed in Mediterranean grassland ecosystems.

The living roof's seasonal patterns were consistent with observations made at natural Mediterranean grassland and semiarid chaparral ecosystems, where peak carbon dioxide uptake usually occurs in late spring, with a NEE range of -2.1 to -0.9 g C m⁻²d⁻¹ (Aires et al., 2007; Luo et al., 2007) (Table 2). However, as seen in Table 3, the magnitudes observed on the living roof were significantly higher than those found in semi-arid chaparral and grassland environments during the dry and pre-growth periods (dry range 0.2-0.4 g C m⁻²; pre-growth range 0.2-0.4 g C m⁻²) (Aires et al., 2007; Luo et al., 2007).

Table 3. Daily average (g C m⁻²d⁻¹) net ecosystem CO₂ exchange (NEE) of a Mediterranean grassland, semi-arid chaparral, and the living roof ecosystems, divided into three different growth periods. Daily averages are based on number of days in each study's individual growth periods.

PERIOD	Mediterranean Grassland Aires et al. (2008)	Semi-arid Chaparral Luo et al. (2007)	CAS Living Roof This study
PREGROWTH	0.4	0.2	3.7
GROWTH	-2.1	-0.9	-1.1
DRY	0.4	0.2	4.3

Over the entire year, maximum daily GPP of the living roof was $-13.24 \text{ g C m}^{-2}\text{d}^{-1}$ and RE $13.21 \text{ g C m}^{-2}\text{d}^{-1}$. In comparison to natural grassland ecosystems, the living roof's magnitudes of GPP were higher than over a Mediterranean grassland in California with reported annual maximums of GPP and RE around -10.1 and $6.5 \text{ g C m}^{-2}\text{d}^{-1}$ (Xu and Baldocchi, 2004), and a grassland near Alberta, Canada, with magnitudes of -8.2 and 4.0 for GPP and RE (Flanagan et al., 2002). However, the living roof's respiration rate was significantly higher, twice respectively three times as high, than the magnitudes reported for the natural ecosystems, turning the roof ecosystem into a daily CO_2 source unlike the compared natural grasslands.

Maximum values over the living roof during the growth period for GPP and RE were -15.0 and $14.0 \text{ g C m}^{-2}\text{d}^{-1}$, respectively. In a previously conducted short-term study on the CAS living roof Thorp (2014) reported a mean daily GPP of -11.7 and RE of $10.2 \text{ g C m}^{-2}\text{d}^{-1}$ over a three month period during spring/summer. Daily GPP was lower compared to this study, which may be because the study period began towards the end of the growing season and included the beginning of the dry season, marked by grass senescence. The estimated living roof's GPP did fall into the seasonal range (-13.6 to $-16.6 \text{ g C m}^{-2}\text{d}^{-1}$) found in a synthesis study of grasslands and other ecosystems by Falge et al. (2002). Mean daily respiration rates of the living roof

measured during the growth period were also significantly higher in contrast to many study sites of comparable natural ecosystems, ranging from 3.4-9.0 g C m⁻²d⁻¹ under regular conditions (Falge et al, 2002). RE values of natural grasslands can be higher however, if the ecosystem is subject to drought conditions (Luo et al., 2007; Aires et al., 2008; Scott et al., 2010). The higher respiration rates reported on the living roof again lead to the assumption that the presence of other than vegetated surfaces (glass atrium roof, concrete viewing deck, building vents) contributed to the carbon dioxide that was measured by EC.

In comparison to similar natural ecosystems (Mediterranean/semi-arid/temperate grasslands, chaparral, and northern coastal shrub/prairie), the CAS living roof is a rather large net annual carbon dioxide source of 1,235 g C m⁻²a⁻¹ to the atmosphere. Most comparable natural ecosystems are a moderate annual carbon sink of a magnitude ranging from -21 to -190 g C m⁻²a⁻¹ (Table 4). Yet even these ecosystems may switch to becoming an annual carbon source during drought events or due to the timing of precipitation (Flanagan et al., 2002; Xu and Baldocchi, 2004); Nagy, 2006; Aires et al., 2008, Scott et al., 2010).

Table 4. Comparison of living roof to similar natural ecosystems net annual (g C m⁻²a⁻¹) carbon dioxide exchange of selected natural ecosystems.

Type of ecosystem	Annual NEE (gC m ⁻² a ⁻¹)	Source
Mediterranean annual Grassland: normal precipitation timing late in season precipitation	-132 29	Xu and Baldocchi (2004)
Semi-arid Chaparral: normal precipitation drought	-155 207	Luo et al. (2007)
Mediterranean C3/C4 Grassland normal precipitation drought	-190 49	Aires et al. (2008)
Semi-desert Grassland normal precipitation drought	-98 25	Scott et al. (2010)
Temperate moist-mixed Grassland	-21	Flanagan et al. (2002)
Warm temperate fully humid Grassland	-113	Nagy (2006)
CAS Living Roof	1235	This study

4.3 Living Roof Respiration

Why is the living roof a modest net CO₂ source? The rich organic soil on the living roof, containing coconut husk and being supplemented with compost, may enhance heterotrophic respiration due to its unnatural amount of organic matter. In addition, supplemental irrigation leading to increased soil moisture may enhance microbial activity. Kaye et al. (2005) found urban soil respiration rates to be 3-5 times higher than natural ecosystems due to increased soil moisture and carbon content in urban soils.

Eddy Covariance measurements may have included CO₂ sources from anthropogenic emissions from human respiration, from fossil fuel combustion for building heating/air conditioning and other activities originating from the CAS museum below. The unnatural asymmetric behavior in the diurnal CO₂ cycle observed, showing an average daily peak CO₂ uptake rate at approximately 10:00 PST, supports this assumption. The California Academy of Sciences opens to the public daily 30 minutes before this effect takes place. It is therefore highly likely that sources stemming from the building below influenced this unusual pattern. This is also supported with the conducted relationship analysis between respiration and soil temperature (Figure 15). Only 27% ($R^2=0.27$) of the 30-minute diurnal ensemble averages could be explained with respiration as a function of soil temperature. The large amount of scatter indicated that not only biological processes contributed to F_{CO_2} measured. If we took the anthropogenic CO₂ emissions measured from the building into consideration, the living roof may have had a mitigating effect and helped offset anthropogenic CO₂ emissions to a certain degree. Were there just concrete instead of vegetation on the roof, F_{CO_2} measured would possibly have been higher.

5.0 CONCLUSION

This study employed the eddy covariance method to obtain measurements of the CO₂ exchange between a living roof and the atmosphere over a period of one year. It quantified diurnal, seasonal, and annual CO₂ exchanges, estimated partitioning of the net CO₂ flux into GPP and RE, and examined environmental controls on their functioning to get a better understanding of ecosystem behavior in the context of anthropogenic CO₂ mitigation in urban areas. Results from observations of a living roof in San Francisco show the following conclusions.

Observed diurnal NEE patterns over the entire study period showed a strong diurnal signal with the roof ecosystem being a net CO₂ source during the night (1.5 mg C m⁻²s⁻¹) and a sink during most of the daylight hours due to vegetation uptake of CO₂ (peak uptake rate of ~-0.2 mg C m⁻²s⁻¹). The living roof was a diurnal CO₂ sink during daylight hours all months of the year. Diurnal patterns showed a net CO₂ uptake by the surface during April and May (-0.4 and -1.3 g C m⁻²d⁻¹) and a daily net CO₂ source the rest of the year, ranging from 0.6-7.3 g C m⁻²d⁻¹. Highest nocturnal respiration rates (~2.0 mg C m⁻²s⁻¹) were observed in the dry period driven by higher summer temperatures. In terms of biological controls, a linear relationship between F_{CO2} and soil temperature as well as GPP and PAR was found. The gap-filled F_{CO2} dataset yielded an annual NEE of 1,235 g C m⁻²a⁻¹ for the living roof. In comparison to

urban ecosystems, only one highly vegetated study site in Baltimore, MD, reported a lower net annual CO₂ flux (361 g C m⁻²a⁻¹), all other urban sites were significantly higher.

When the year was divided into three Mediterranean biome periods of growth, the living roof's seasonal patterns were consistent with observations made at natural Mediterranean grassland and semiarid chaparral ecosystems, with peak CO₂ uptake occurring in late spring (Aires et al., 2007; Luo et al., 2007). The roof ecosystem was a diurnal CO₂ sink on the magnitude of ~-1.1 g C m⁻²d⁻¹ during the growth period. However, the large daily CO₂ values of ~4.3 g C m⁻²d⁻¹ and ~3.7 g C m⁻²d⁻¹ observed during the dry and pre-growth periods were considerably higher than those found in semi-arid chaparral and grassland environments (dry range 0.2-0.4 g C m⁻²; pre-growth range 0.2-0.4 g C m⁻²) (Aires et al., 2007; Luo et al., 2007).

The estimated living roof GPP during the growth period of -15.0 g C m⁻²d⁻¹ fell into the seasonal range (-13.6 to -16.6 g C m⁻²d⁻¹) found in a synthesis study of grasslands and other ecosystems by Falge et al. (2002). The daily respiration rates (14.0 g C m⁻²d⁻¹) estimated however, were much higher in contrast to many study sites of comparable natural ecosystems, ranging from 3.4-9.0 g C m⁻²d⁻¹ under regular conditions (Falge et al, 2002).

There are limitations associated with this study including the uncertainty of the measured respiration rates. It is suspected that the rich organic soil on the living roof and increased soil moisture due to supplemental irrigation may have enhanced heterotrophic respiration. Also, the unnatural asymmetric behavior observed in the diurnal CO₂ cycle throughout the year supports the assumption that eddy covariance measurements may have included anthropogenic CO₂ emissions from the CAS museum below. This assumption was also supported with the conducted relationship analysis between respiration and soil temperature. However, factors that may have elevated atmospheric CO₂ concentrations could also have changed the CO₂ sequestration rates by the vegetation, adding to the uncertainties.

CO₂ uptake rates were smaller than respiration rates, turning this site into an annual net CO₂ source. If it were a concrete roof without vegetation instead, F_{CO_2} measured would likely have been higher. Considering the earlier described anthropogenic CO₂ emissions that may have been included in the respiration rates, the living roof may have had a partial mitigating effect in offsetting anthropogenic CO₂ emissions. This study did not take CO₂ emissions associated with roof maintenance into account (e.g., emissions from trucks transporting weeds and plant litter from the roof to composting locations several times a year).

This study is unique in the context of urban CO₂ flux research because of the characteristics of the study site on a living roof. Further work is needed to be able to better differentiate the sources measured on a living roof, e.g. by using chamber systems measurements of CO₂ effluxes or the isotopic-tracer technique to identify CO₂ mixing ratios. In terms of vegetation, the plant species composition influences the magnitude of carbon sequestration (Getter et al., 2009), showing the importance for more studies to be conducted using a diverse vegetation cover in similar but also other climatic zones. Finding a large enough, flat and homogenous study site to obtain eddy covariance measurements, remains a big challenge, however.

Even though the CAS living roof was not a net annual CO₂ sink, it clearly showed the potential for anthropogenic CO₂ mitigation. With urban areas further expanding and increasingly affecting the global carbon dioxide exchange in its course, it is important to integrate such analysis in the decision making process of urban planning. Such research data represents a useful tool for decision makers and urban planners in the development of sustainable growth and emission offset strategies in urbanized areas.

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7.0 APPENDICES

7.1 List of plant species with corresponding percent cover area on the living roof of the California Academy of Sciences in San Francisco, CA (Lavender, 2014)

Plant species	Latin name	Observations	% cover
bare soil	NA	44	8.8%
beach strawberry	<i>Fragaria chiloensis</i> ,	164	32.9%
bur clover	<i>Medicago</i>	7	1.4%
California bent grass	<i>Agrostis densiflora</i>	59	11.8%
California fuchsia	<i>Epilobium canum</i>	6	1.2%
California poppy	<i>Eschscholzia californica</i>	1	0.2%
California sweet grass	<i>Hierochloe</i>	15	3.0%
coast dudleya	<i>Dudleya caespitosa</i>	1	0.2%
common yarrow	<i>Achillea millefolium</i>	28	5.6%
dandelion	<i>Taraxacum</i>	7	1.4%
fireweed	<i>Chamerion angustifolium</i>	17	3.4%
foxtail fescue	<i>Festuca</i>	35	7.0%
golden-eyed grass	<i>Sisyrinchium californicum</i>	8	1.6%
gumweed	<i>Grindelia</i>	10	2.0%
leaf litter	NA	16	3.2%
lupin	<i>Lupinus</i>	6	1.2%
nutgrass	<i>Cyperus rotundus</i>	8	1.6%
scorpionweed	<i>Phacelia</i>	10	2.0%
plantain weed	<i>Plantago major</i>	2	0.4%
purple needle grass	<i>Nassella pulchra</i>	2	0.4%
scouringrush horsetail	<i>Equisetum hyemale</i>	4	0.8%

seaside daisy	<i>Erigeron glaucus</i>	9	1.8%
seep monkeyflower	<i>Mimulus</i>	14	2.8%
self heal	<i>Prunella</i>	15	3.0%
sowthistle	<i>Sonchus</i>	7	1.4%
yellow primrose	<i>Primula vulgaris</i>	3	0.6%