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Anthropogenic and natural CO_2 emission sources in an arid urban environment

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"Capsule": *Human and automobile sources produced more than 80% of the carbon dioxide inputs into an urban landscape in a desert environment.*

Abstract

Recent research has shown the Phoenix, AZ metropolitan region to be characterized by a CO_2 dome that peaks near the urban center. The CO_2 levels, 50% greater than the surrounding non-urban areas, have been attributed to anthropogenic sources and the physical geography of the area. We quantified sources of CO_2 emissions across the metropolitan region. Anthropogenic CO_2 emission data were obtained from a variety of government and NGO sources. Soil CO_2 efflux from the dominant land-use types was measured over the year. Humans and automobile activity produced more than 80% input of CO_2 into the urban environment. Soil CO_2 efflux from the natural desert ecosystems showed minimal emissions during hot and dry periods, but responded rapidly to moisture. Conversely, human maintained vegetation types (e.g. golf courses, lawns, irrigated agriculture) have greater efflux and are both temperature and soil moisture dependent. Landfills exhibited the most consistent rates, but were temperature and moisture independent. We estimate the annual CO_2 released from the predominant land-use types in the Phoenix region and present a graphical portrayal of soil CO_2 emissions and the total natural and anthropogenic CO_2 emissions in the metropolitan region using a GIS-based approach. The results presented here do not mimic the spatial pattern shown in previous studies. Only, with sophisticated mixing models will we be able to address the total effect of urbanization on CO_2 levels and the contribution to regional patterns.

Keywords: Urbanization; Carbon dioxide; Soil CO_2 efflux; Geographic information systems (GIS); Land-use

1. Introduction

Over 30% of the world's populations live in arid and semiarid regions and it is expected that the proportion and total numbers of individuals in these dry areas will increase, adding to the urbanization land-use changes around the globe. Additionally, whilst it is known that the total carbon pools and fluxes in the natural arid and semiarid ecosystems per unit area are small, the impact of human occupancy over this huge area of the earth will be significant. The metropolis of Phoenix, Arizona provides an excellent example to demonstrate the effect of urbanization with a population growth rate of >35% from 1990 to 1999 (US Census Bureau, 2000). Increasing population results in the expansion of the urban area into surrounding natural and agricultural ecosystems yielding changes in climate and ecosystem processes. The effects of humans and urbanization on ecosystem processes can be better understood using the urban ecosystem as a study tool in comparison with rural "control" sites (Groffman et al., 1995). The Phoenix Metropolitan area provides an opportunity to examine urbanization and climate change effects because of measurable "heat island" effects and elevated CO_2 levels (Balling and Brazel, 1987, 1988; Idso et al., 1998, 2001).

Fann et al. (1998) reported a large terrestrial carbon sink in North America, although its magnitude has since been disputed (e.g. Holland and Brown, 1999; Field and Fung, 1999). A robust understanding of the global carbon budget requires an understanding of the ecological mechanisms responsible for carbon source–sink relationships. On a regional basis, these relationships may have a high degree of variability based on the spatial configuration of the landscape and its legacy (Houghton et al., 1999; Caspersen et al., 2000). The terrestrial spatial variation is further complicated by the climate derived temporal changes (Bousquet et al., 2000; Fung, 2000). Perhaps nowhere is this variability more evident than in urban ecosystems that are composed of a *mélange* of different patch types ranging from totally non-biological and completely anthropogenic supported to natural ecosystems. Many localized or regional models assume that the local carbon cycle is in steady

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state and changes in fluxes are dictated by climate. The urban carbon cycle has its own driving forces, significantly different than those of natural ecosystems. The total carbon pools in the natural arid and semiarid ecosystems per unit area are small, but the impact of human populations over this large area of the earth may be significant. Urbanization and agriculture drastically changes the biological structure of arid and semiarid ecosystems due to the water and energy subsides causing changes in carbon stocks and fluxes. A change in the soil carbon pool could result in significant changes in atmospheric CO_2 concentrations because the soil carbon reservoir contains more than twice the carbon in the atmospheric carbon pool (Raich and Potter, 1995; Falloon et al., 1998). Urbanization increases CO_2 concentrations that, in natural ecosystems, results in varying responses (Schimel, 1995), and alters precipitation patterns and increases temperatures due to a ‘‘heat island’’ effect. In desert ecosystems, possible changes in precipitation patterns may have a greater impact on productivity, soil respiration, and soil organic matter because arid and semiarid ecosystems are more dependent on precipitation than temperature (Smith et al., 1994; Conant et al., 1998).

Recent research has identified significant CO_2 increases across the Phoenix metropolitan region as compared to the surrounding rural areas. This led us to the key question: ‘‘How are local CO_2 concentrations affected by human activities in an arid urban environment?’’ To address this question, we are conducting a carbon source study evaluating anthropogenic and natural sources of carbon in Phoenix, AZ. As part of this study, we are investigating the annual soil CO_2 efflux in relation to different land use types and their water use regimes. As in most ecosystems, the soil contains the major pool of organic C in these systems. However, whether the soil becomes a significant source or sink for atmospheric CO_2 depends on its ecosystem type, successional stage, and geographic location (Schimel et al., 1994; Trumbore et al., 1996; Schlesinger and Andrews, 2000). Soil respiration may represent a sizable contribution of atmospheric C from these urban lands, but has yet gone unmeasured. Thus, we are evaluating soil CO_2 efflux of the land use types that dominate the Phoenix metropolis.

2. Materials and methods

2.1. Regional description

The Phoenix Metropolitan area lies within the upper Sonora Desert (Brown, 1982) and much of the Phoenix valley was once covered by open stands of creosote bush (*Larrea tridentata*) and burrsage (*Ambrosia deltoidea*). Its soils are predominantly Aridisols, light colored mineral soils that are evidence of the low C sequestration (Hendricks, 1985). These soils can vary from 0.2 to 0.5% organic C, dependent on vegetative cover. In contrast, soils of the agricultural crops can vary from 0.5 to 1.1% C, again dependent on type of crop (e.g. Leavitt et al., 1996; Prior et al., 1997). Residential lawns under constant grass cover can be up to 2% organic C (Klopatek, unpublished data). Thus, nowhere in the United States is the effect of water more evident than in a comparison of the C storage in three dominant patch types—desert, residential and agricultural. The desert system is highly dependent on spatially and temporally variable natural precipitation, while agriculture in this region is virtually dependent on irrigation.

The surrounding native desert and agricultural lands are rapidly being converted into residential subdivisions, expanding the radius of the urban area at a rate of nearly 1 km per year (Morrison Institute of Public Policy, unpublished data). Urbanization has caused Phoenix to characterized by a CO_2 dome that peaks near the urban center (Fig. 1a, b). The concentrations of CO_2 in Phoenix are high, not just because of anthropogenic sources, but also because of the physical geography and meteorology of the area. Contributing the

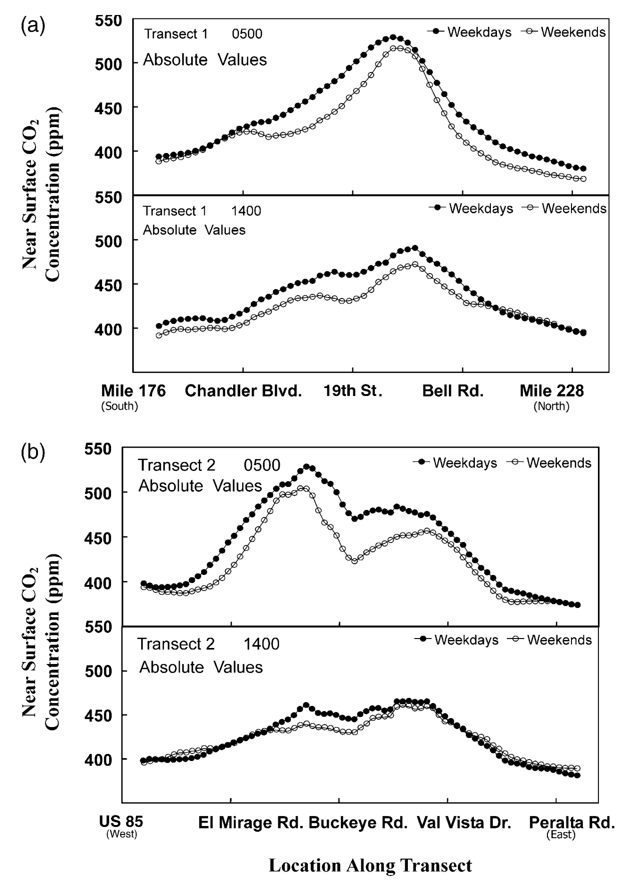

Fig. 1. Mean near surface CO_2 concentrations for two weeks in January, 2000. (a) Transect 1 represents the north–south route through the central portion of Phoenix. (b) Transect 2 represents the east–west route through the central portion of Phoenix. (Modified from Idso et al., 2001).

dome effect is a pronounced daytime mountain–valley mesoscale thermal circulation (Davis and Gay, 1993). During the night-time hours, and particularly during the winter season, the opposite flow pattern dominates resulting in common night-time inversions. These two factors play a significant role in the spatial distribution of CO_2 throughout Phoenix, and we focus on the sources of CO_2 contributing to the CO_2 dome.

Changes in land use can drastically change the carbon balance of an ecosystem. We chose to investigate how different sources of CO_2 contributed to the CO_2 dome. The initial sources of CO_2 we investigated were land-based and anthropogenic. Of the land based sources, we measured the soil CO_2 efflux on native desert and human maintained landscapes such as golf courses, landfills, mesic and xeric landscapes, and cotton, alfalfa, and citrus agricultural sites. The anthropogenic sources we documented included vehicle, airplane and power plant emissions, and human respiration. An integrative approach is necessary to answer these questions because of the anthropogenic and ecosystem sources of carbon in an urban area. We use GIS to address these questions and provide a spatial representation of the documented CO_2 sources in Phoenix, Arizona. The base for the spatial representation of CO_2 was a land-use data theme created by Maricopa Association of Governments (MAG) in 1996.

2.2. Soil CO_2 efflux data

Soil CO_2 efflux data were collected using an infrared gas analyzer with a soil chamber (model LI-6400-09, Li-Cor, Lincoln, NE). Four groups of 3 PVC collars (ID = 10 cm) were inserted into the soil surface at each site in May 2000. Each group of collars was randomly placed in a location at each site. At each site, soil temperature, soil moisture and soil respiration were measured at monthly intervals from June 2000 to May 2001.

Soil temperature (10 cm depth) was measured using a thermocouple inserted into the soil adjacent to the soil CO_2 chamber. The soil temperature was recorded simultaneously with the soil CO_2 efflux measurements. Surface soil moisture (10 cm depth) was determined after drying (70°C) samples taken concurrently with measurements of soil CO_2 efflux.

2.3. Anthropogenic sources of CO_2

Sources of anthropogenic CO_2 identified in this study are human respiration, vehicle, power plant and airplane emissions. The human respiration value of 31.5 mol CO_2/person/day was calculated with the following assumptions: an average person weighs 70 kg, metabolic rate per day is about 2 times resting, and the only metabolic fuel used is a carbohydrate. Population data were obtained from ESRI's 1990 compiled Census data that are based on the 1990 US Population Census (ESRI, 1997; these were the only spatially partitioned data available, and thus are nearly 40% less than current 2000 figures). From this file we extracted the total population for 1997 from all census tracts in Maricopa County, AZ. Human respiration values were then applied to the population data, and these values represent a net source of CO_2 as most food is imported into the region.

The average weekly traffic (AWT) data were digitized from MAG's 1998 weekly traffic map into an ArcINFO coverage, and converted into an ArcView shapefile. The 1999 Vehicle Emissions values were obtained from the Arizona Department of Environmental Quality (ADEQ). CO_2 values were averaged for all vehicles tested that year and were multiplied by the AWT in the AWT shapefile.

The location of Sky Harbor Airport and power plants were identified on the MAG land-use file and were converted into new shapefiles. The airplane emissions data for take-off and landing were compiled from an EPA emissions inventory report (1992), and the flight traffic for Sky Harbor Airport was obtained from FAA (1999). Other airports were not included because of lack of flight traffic data and minimal flight traffic compared with Sky Harbor Airport. Monthly data for power plant emissions of CO_2 (tons month^{-1}) were obtained directly from Arizona Power Service (APS) and the Salt River Project (SRP). Both sets of emissions data were then applied on a per area basis to the land covers.

2.4. Data evaluation

Estimates of impervious land for each land-use type were provided by the Central Arizona Phoenix–Long Term Ecological Research (CAP-LTER) project. These estimates were combined with visual estimates obtained by comparing randomly selected polygons of each land use type with aerial photographs of Phoenix. The ratio of different soil CO_2 effluxes for an individual land-use type was also obtained from the CAP-LTER project data, comparison with a land cover reclassification image (Stephanov, 2000; Stefanov et al., 2000), and visual estimates with aerial photographs. Daily and annual CO_2 efflux values are based on once monthly measurements despite the fact that soil respiration is largely influenced by soil moisture. Unfortunately, no continuous soil moisture data is available for any areas throughout Phoenix. The soil CO_2 efflux rates for each land-use type were then estimated by multiplying the daily rate by 365 days. The total annual soil CO_2 efflux was calculated by multiplying the yearly rate by the total area of each land-use type.

Similar methods were applied to the other CO_2 source variables. Once all of the GIS themes had a rate of CO_2 emissions, each theme was converted into a grid. In the grids lacking continuous data, the no data classification were converted to a value of zero to allow the grid layers to be represented in the final output. All of the different source covers were then overlayed to obtain a final CO_2 source cover value.

3. Results

3.1. Soil CO_2 efflux

The soil CO_2 efflux ranged from 1.79 to 51.87 g CO_2 m^{-2} day^{-1} for the different land-use types measured (Fig. 2). The desert canopy (area underneath the shrub canopy) and interspace (area between shrub canopies) showed the lowest rate of CO_2 evolution. The vacant (abandoned agricultural) land and xeric landscaping land-uses also resulted in low soil CO_2 efflux rates. Mesic landscaping (grass lawns), golf courses and all agricultural land uses resulted in high rates of CO_2 evolution. Landfills exhibited the highest rates of CO_2 evolution. The efflux (excluding landfills) generally increased with increasing soil moisture ($R^2 = 0.6347$, $P < 0.0001$). Soil temperature had no significant effect on the efflux ($P = 0.7798$).

3.2. GIS analysis

All of the soil CO_2 efflux rates were applied to a land-use cover in a GIS using ArcView to portray the spatial distribution of the soil CO_2 efflux (Fig. 3a). The highest rates actually occur around the borders of Phoenix in the agricultural areas. With the exception of the industrial regions, the desert has a very low rate compared to human maintained landscapes such as residential areas. Some of the low rates for land uses result from large portion of the land use type being covered with impervious surfaces such as buildings, paved roads and parking lots. The total CO_2 emissions for each land-use type are given in Table 1. Agriculture accounts for 60.9% of the total soil CO_2 emissions from land-based sources. Native desert is the second largest source (18.2%), but it has the largest area. Residential land-uses (10.3%) and golf courses (5.9%) are also large contributors of CO_2.

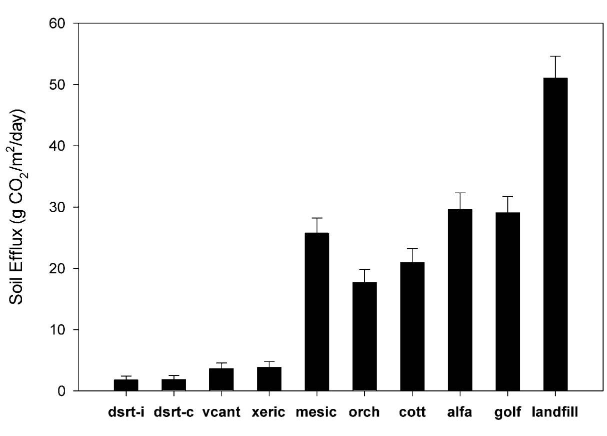

Fig. 2. Mean and standard error of the daily soil CO_2 efflux for different land use types in the Phoenix metropolitan region.

Vehicles are by far the largest contributor of CO_2 documented in this study (Table 2), while soil respiration is the second largest contributor of CO_2 in the Phoenix urban ecosystem. Because of the linear relationship of the vehicle emissions to the main arterial roadways, it is impossible at this time to show the mixing effects with other sources and subsequent dispersion (Fig. 3b).

4. Discussion

Efflux of CO_2 from soils is a function of the activity of autotrophic roots and associated rhizosphere organisms (e.g. mycorrhizae), heterotrophic bacteria and fungi acting primarily as decomposers, and soil fauna. The main factors controlling soil CO_2 efflux are soil temperature, moisture, organic C and vegetation density. Temperature should be one of the strongest factors influencing the soil CO_2 levels (Lundegarth, 1927), but soil moisture seems to be the largest contributing factor to soil CO_2 efflux in arid regions such as Phoenix. Water subsidies on many of the land-use types are the largest single factor increasing the soil CO_2 efflux. During the summer months, temperature has minimal influence on the rate of CO_2 evolution. During the winter months, the influence of temperature on soil respiration rates increases, but water remains the most influential factor driving soil respiration. In an ongoing experiment, soil CO_2 efflux values increased more than 50 times in desert environments with irrigation. While decomposition within landfills in this region is slow (Rathje and Murphy, 1992), the rates of their CO_2 efflux is significant, despite that they do not follow the pattern of the other land-use types that exhibited the significant influence of soil moisture.

While we measured the CO_2 efflux from the ecosystem, we did not account for the net flux of carbon, or the CO_2 interactions with the vegetation. Wentz et al. (in press) reported distinct patterns across the urban area related to vegetation patterns. When investigating the spatial distribution of CO_2 emissions from soils, the pattern of the CO_2 dome is not mimicked. The largest regions of soil CO_2 emissions are located in the agricultural regions on the border of Phoenix. The residential and business land-uses located in the center of Phoenix have intermediate values when compared to native desert. As a result, soil CO_2 emissions do not appear to be a large contributing factor to the CO_2 dome. This is further supported by soil CO_2 emissions only accounting for 15.8% of the total CO_2 emission for

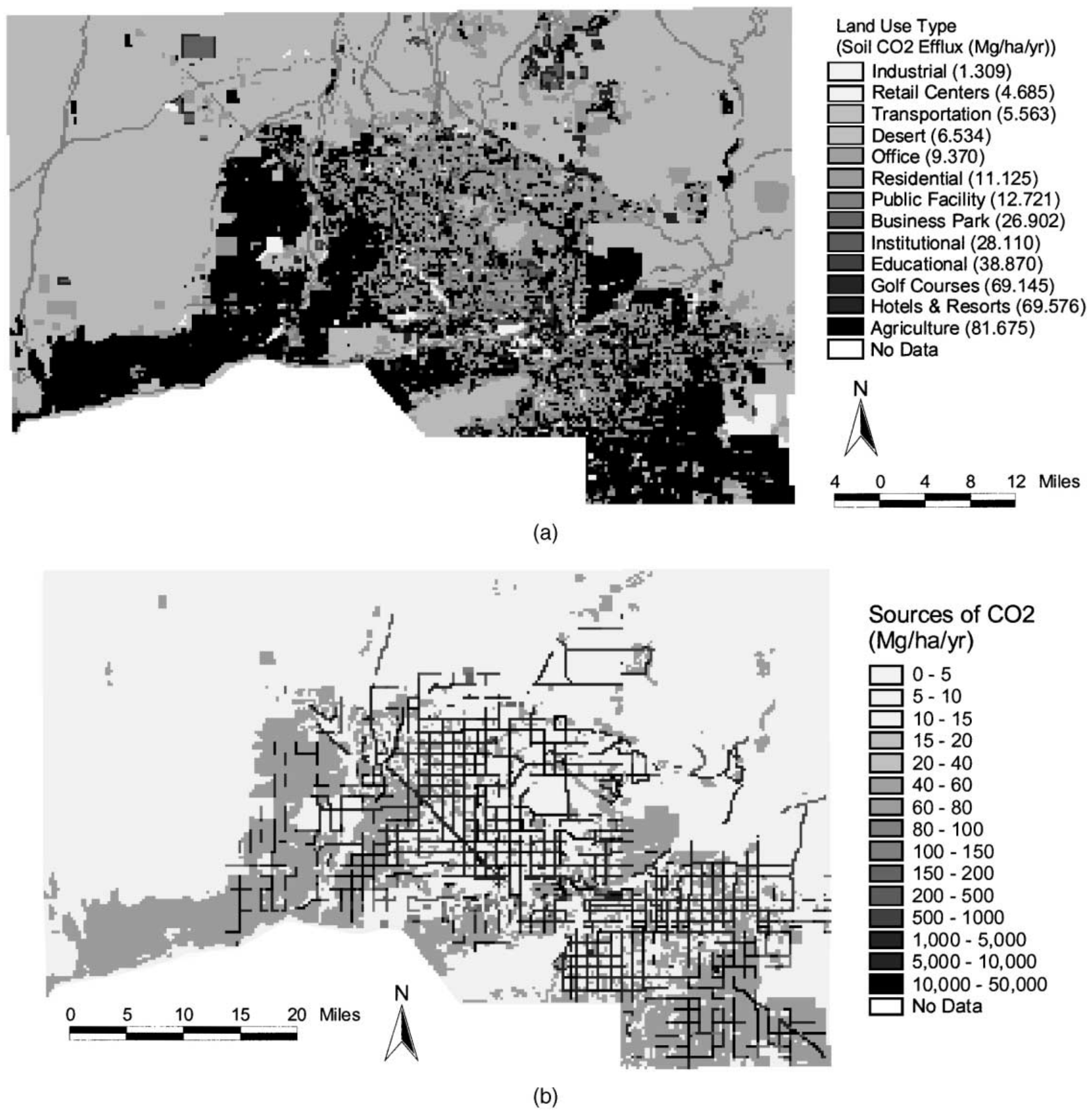

Fig. 3. (a) Total annual soil CO_2 efflux for different land use types in the Phoenix metropolitan region. (b) Total annual CO_2 emissions from vehicles, power plants, airports, human respiration and soil respiration in the Phoenix metropolitan region. The scale is exponential in order for all of the sources to be visually represented.

Phoenix, AZ. In addition, some of the CO_2 released by soils is taken up through photosynthesis in these systems. Most likely, there is still a net CO_2 flux. In the summer months, temperatures are quite high (daily highs ranging from 38 to over 45°C) which may lead to further CO_2 emissions through photorespiration, especially in non-desert landscapes.

Alternately, anthropogenic sources of CO_2 appear to be largely responsible for the CO_2 dome present in the Phoenix valley. Vehicles are by far the largest contributor (79.9%) of CO_2 in Phoenix. Human respiration, contributing as much CO_2 as the five power plants in Phoenix, is the only source that does not represent a net source of CO_2 to the atmosphere. Instead, it represents imported food resulting from CO_2 removal from elsewhere in the atmosphere. The simple presence of humans in an urban area has a dramatic effect on the carbon balance of an ecosystem. Although minor, landfills also represent the return of imported carbon to the atmosphere in the case of paper and food waste. Conversely, they also contribute to increasing CO_2 due to degrading fossil fuel based wastes (i.e. plastics).

5. Conclusions

Urbanization has more than just a land use change effect on arid landscapes. Urbanization may change ecosystem function by changing the biogeochemical cycles and driving forces (e.g. temperature, carbon, and precipitation). In arid environments such as Phoenix, water is the limiting factor in which natural environments have evolved. With water subsidies, humans are changing the competitive advantage of the natural

Table 1
Soil CO_2 efflux rates for different land-use types in Phoenix, Arizona

Land use type	Area (ha)	Soil CO_2 efflux (Mg/ha/year)	Total CO_2 (Mg/year)
Agriculture	100,186	81.675	8,182,739
Desert	375,385	6.534	2,452,577
Residential	120,235	11.125	1,381,414
Golf course	11,476	69.145	793,566
Business park	5706	26.902	153,501
Educational	3836	38.870	149,084
Transportation/water	21,218	5.880	123,424
Retail centers	9992	4.685	46,816
Institutional	1588	28.110	44,630
Hotels, motels, resorts	585	69.576	40,698
Public facility	3091	12.721	39,314
Warehouse/industrial	14,592	1.309	19,098
Office	1420	9.370	13,306
Total	669,310		13,440,167

Table 2
Total annual CO_2 emissions for different sources throughout the Phoenix metropolitan area

Source	Total CO_2 emissions (Mg/year)	Proportion (%)
Vehicles	67,737,789	79.9
Airplanes	52,393	<0.1
Power plants	1,841,657	2.2
Landfills	391,230	0.5
Human respiration	1,333,625	1.6
Soil respiration	13,440,170	15.8
Total		100.0

community structure. Additionally, water subsidies will further exacerbate increasing CO_2 levels due to drastic increases in soil CO_2 efflux in irrigated landscapes. Even widely increasing xeric landscaping procedures will increase the soil CO_2 efflux contribution compared with the native desert. Urbanization also increases temperature, which increases the stress on an already stressed ecosystem. Under these situations, higher temperatures may actually cancel out any CO_2 fertilization effects on the ecosystem.

The data presented here is still in its preliminary stages. The information from investigations such as this can be used to predict future changes in arid and semi-arid landscapes as a result of urbanization. It is known that the total C pools in the natural arid and semiarid ecosystems per unit area are small, but the impact of human occupancy over this huge area of the earth may be significant. It is predicted that urbanization will affect extensive land cover and land-use changes in semi-arid and arid lands. Thus, it is imperative that we understand how significantly changing the biological structure of these ecosystems through agriculture and urbanization by subsidization with water and energy changes the C stocks and fluxes. Assessing the role of land-use on the biogeochemical cycle is necessary to evaluate the integrated effects of humans and the carbon cycle (Sarmiento and Wofsy, 1999). This study has just examined the inputs to the carbon cycle, but this and further investigations will further contribute to the understanding of the effects of urbanization on native landscapes. The results of this study will also provide a greater understanding into the mechanisms of ecosystem processes and how desert ecosystems may respond to urbanization pressures.

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