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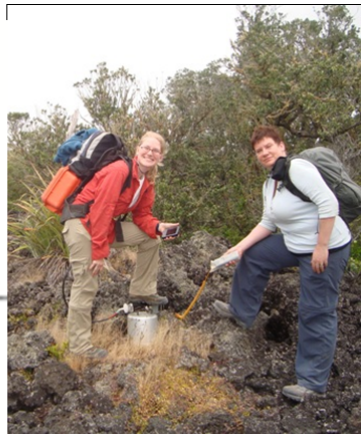

Soil Gas CO_2 Concentrations & CO_2 Fluxes in the Auckland Volcanic Field

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Soil Gas CO_2 Concentrations & CO_2 Fluxes in the Auckland Volcanic Field

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ABSTRACT

Numerous studies have shown that anomalously high soil gas CO_2 fluxes and concentrations may be precursors to volcanic activity, and that faults or fractures may act as conduits for gases and magma to the surface. The Auckland Volcanic Field (AVF) is a dormant monogenetic basaltic field located in Auckland, New Zealand, on which there have been no previous studies of soil gas CO_2 fluxes or concentrations; atmospheric CO_2 is likewise not monitored. As part of the DEtermining VOlcanic Risk in Auckland project, soil gas CO_2 fluxes and concentrations were measured in seven transects spanning various settings (e.g. urban, rural, areas of known or suspected faults, areas of no suspected faults) in the AVF over one week in November 2010. There were two key goals for this pilot study: establish a baseline soil gas CO_2 flux and concentration for the AVF; and to attempt to detect subsurface structures such as faults that may act as a control on future vent locations. During this study, 72 measurements of CO_2 concentrations ranged from 393 parts per million (ppm) to 10,140 ppm; 443 fluxes varied from 0 to 108.7 g $m^{-2}d^{-1}$. Using a graphical statistical approach, two populations of CO_2 fluxes were identified. Both may represent the biological CO_2 production background flux in the AVF, with the main control attributed to soil permeability. Differences in urban versus rural fluxes may be attributed to greater infiltration of air with higher CO_2 concentrations in urban areas. No faults could be discerned using soil gas CO_2 fluxes or concentrations; however, a heteroscedastic 2 tail test indicates that there is a significant difference between fault and no-fault transects. These results hint at interesting variations in soil CO_2 across Auckland; future work includes expanding the study area and identifying the sources of CO_2 via ^{13}C isotope analysis.

1.0 INTRODUCTION

1.1 Background and impetus for study

The Auckland Volcanic Field (AVF) is a dormant monogenetic basaltic field comprising approximately 50 volcanoes spanning a ~360 km^2 area in Auckland, New Zealand's most populous city (Fig. 1) (Kermode 1992). Individual eruptions from monogenetic volcanoes usually impact a smaller footprint compared to those from polygenetic volcanoes but they can be very destructive in a ~5 km radius around the vent, especially in populated regions (Delgado-Granados and Villalpando-Cortes 2008). Given the young age of this field (< ~250,000 years) as compared to analogue monogenetic fields such as the South Auckland Volcanic Field, future eruptions are expected, with an estimated warning period as short as a few days (Sherburn et al. 2007). Furthermore, the varied characteristics of this and other monogenetic fields make it difficult to predict the timing and location of future eruptions (Delgado-Granados and Villalpando-Cortes 2008). In light of this information, New Zealand's Ministry of Civil Defence and Emergency Management staged a mock eruption scenario, called Exercise Ruaumoko, in March 2008 to test preparedness.

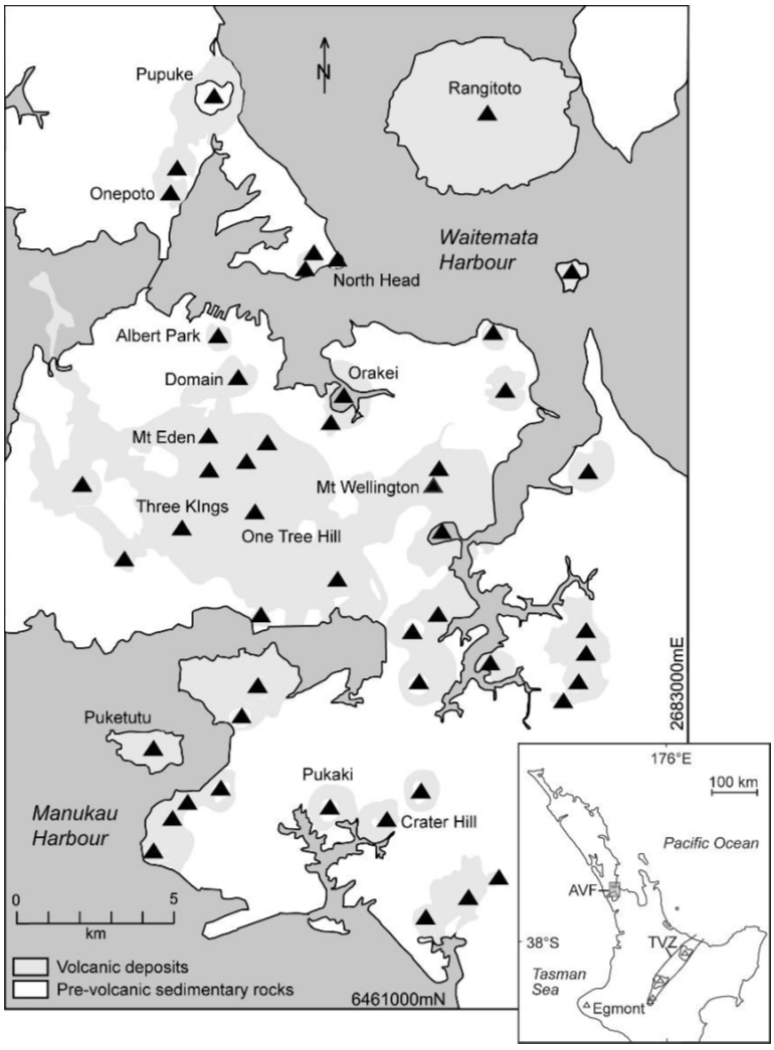

Figure 1. The location of the volcanoes contained within the Auckland Volcanic Field; inset: location of the AVF within the North Island of New Zealand. From Constantinescu and Lindsay (2010).

During Exercise Ruaumoko, soil gas emission measurements, particularly CO_2, were a key part of the simulated GeoNet response. After signs of unrest (seismic activity) were detected during the Exercise, a team of scientists was tasked with making measurements of soil gas flux and monitoring any changes from background levels near the epicentres. Because of the likelihood of CO_2 emissions in a future eruption, the presence and level of CO_2 emissions also represented a key input in an eruption forecasting model tested by volcanologists during the Exercise (Lindsay et al. 2010). It was assumed that any increases in gas emissions over background levels would be reported by a member of the public due to the high population density of Auckland, however, while the presence of increased volcanic H_2S or SO_2 gases may be easily sensed by smell at concentrations above 0.3 ppm and 0.5 ppm, respectively, CO_2 increases may go completely unnoticed (http://www.atsdr.cdc.gov/ToxProfiles/tp114-c4.pdf; http://www.chemtradelogistics.com/MSDS/Sulfur_Dioxide-English.pdf).

No quantitative measurements of typical flux or concentrations in soil gas CO_2 in the Auckland area exists at present (Lindsay et al. 2010; J. Salmonds, pers. comm.; L. Schwendenmenn, pers. comm.). Though atmospheric CO_2 concentrations are monitored in Wellington and nation-wide estimates for atmospheric concentrations CO_2 are available, currently, atmospheric and/or soil gas CO_2 in Auckland are not monitored through any government agency. There is therefore no basis for comparison to ascertain an 'anomalous' CO_2 concentration or flux. Early detection of anomalies in soil gas CO_2 concentrations could improve lead time in an impending eruption, which may be crucial to saving lives as the warning period before eruptions could be brief (Smith et al. 2008). At the conclusion of Exercise Ruaumoko, the volcanology team suggested future improvements such as monitoring soil gas emissions in the AVF to establish a baseline CO_2 flux. Under the umbrella of the DEtermining VOlcanic Risk in Auckland (DEVORA) project, this pilot study is the first step in establishing a methodology for monitoring soil CO_2 in the AVF.

In addition to aiding volcanic prediction techniques, soil gas CO_2 anomalies have been used to map subsurface features, such as active faults and fissures (Fu et al. 2005; Baubron et al. 2002; Mori et al. 2001). These structures are thought to be natural conduits through the crust for gases from deep-seated sources (Baubron et al. 2002). Some volcanic fields exhibit vent clusters or lineaments along fault lines, indicating that these crustal weaknesses can also act as preferential paths for magma in volcanic fields (Delgado-Granados & Villalpando-Cortes 2008; Connor et al. 1992; Hasenaka & Carmichael 1985). As a monogenetic field with little to no consistent vent distribution trends, the location of future eruptions in the AVF is currently unknown (e.g. Allen & Smith 1994; Magill et al. 2005; von Veh & Nemeth 2009; Bebbington & Cronin 2010). Based on patterns seen in other fields, it is suspected that new vents will occur along existing fault lines, but these are also relatively unknown in Auckland due to the heavy urbanisation and low seismic activity in the area (Spoerli & Eastwood 1997). Therefore, a second aim of this study is to identify anomalies in soil gas CO_2 in Auckland, especially along suspected fault lines, to potentially identify active faults through which future eruptions in Auckland may take place.

1.2 Sources of CO_2 and influencing factors

CO_2 in soil originates from several sources: root respiration, decomposition of organic matter, atmospheric infiltration, magmatic degassing, or the metamorphosis or dissolution of carbonate (Heiligmann et al. 1997). Atmospheric conditions, including soil moisture, air and soil temperature, barometric pressure and wind speed, and geologic setting (soil properties, fault and fracture density, topography) play large roles in controlling the flux from and the concentrations within the soil (Chiodini et al. 2008; Reimer 1980; Hinkle 1994), with one study identifying air temperature and soil humidity as the most important influences on soil flux (Granieri et al. 2003). Due to the many influences and sources, soil CO_2 concentrations and fluxes of CO_2 are highly variable, diurnally, seasonally, and even within a small area (Gunn 1982; Maljanen et al. 2002).

1.3 Use of soil gas surveys for monitoring volcanic regions

Volcanic gas diffusing from the soil is usually comprised of CO_2, H_2, He, Ar, Rn, sometimes CH_4 and CO, and very rarely, SO_2 and H_2S (Baubron et al. 1991). In active polygenetic volcanoes, CO_2 is often diffusively emitted during and between eruptive cycles. As CO_2 is one of the most abundant gases in and also one of the first gases to exsolve from magma, monitoring the soil gas CO_2 concentrations and CO_2 fluxes can reveal anomalous increases which may be one of the first signs of an impending eruption (Mori et al. 2001; Bruno et al. 2001; Granieri et al. 2003). Moreover, measurements of soil gas CO_2 can usually be made in safe and accessible areas, meaning that over a long and continuous monitoring period, anomalies can be detected (Baubron et al. 1991). Due to these properties and our ability to distinguish its sources isotopically, CO_2 is one of the most studied of the volcanic gases emitted through the soil and is monitored on volcanoes world-wide (Cerling et al. 1991; Granieri et al. 2003). Surveys of soil gas CO_2 fluxes and concentrations have been performed in many volcanic settings since the early 1980s, including Japan, Italy, Hawaii, Greece, Mexico, and New Zealand (e.g. Carbonnelle & Zettwoog 1982; Finlayson 1992; Giammanco et al. 1995; Allard et al., 1991; Baubron et al., 1990; Farrar et al., 1995; Chiodini et al., 1996, 1998; Gerlach et al. 1998; Notsu et al. 2006; Hernandez et al. 2001; Giammanco et al. 1998; Barberi and Carapezza 1994).

Chiodini et al. (2008) summarized the results of several soil CO_2 flux surveys of many volcanoes and geothermal areas. The background CO_2 flux ranges from 0.34 to 94 g $m^{-2}d^{-1}$ (with an average of ~ 23 g $m^{-2}d^{-1}$) and the flux from actively volcanic areas ranges from 62 to 9,500 g $m^{-2}d^{-1}$. In volcanic regions, soil gas CO_2 concentrations can be up to 90 % by volume (Allard et al. 1991). No correlations are usually found between fluxes and concentrations, although Baubron et al. (1991) mentions that flux and concentrations should be linked in steady-state systems. They also report that in areas where no prior anomalies are present, combined CO_2 soil concentrations of 10%, 10 ppm He and 3,000 picocuries per liter Rn at 1 m depth is a possible indicator of impending volcanic activity. The use of gas fluxes to monitor volcanic areas may reflect increased output more readily than soil gas concentrations.

Only one other study of soil gas CO_2 flux in an active monogenetic field exists; Delgado-Granados and Villalpando-Cortes (2008) measured soil gas CO_2 fluxes in the Chichinautzin Volcanic Field, Mexico, to determine background fluxes for the field. They report background soil gas CO_2 fluxes from 0 to 8.6 g $m^{-2}d^{-1}$; the authors considered a flux of 16.1 g $m^{-2}d^{-1}$ as 'anomalously high' in an area that was subsequently tectonically active.

Other studies report varied results:

In Rotorua, New Zealand, a study over a geothermal field found a background CO_2 concentration of 5.2 mole % at 1 m depth, with geothermally influenced concentrations ranging from 10 to 70 mole % (Finlayson 1992). Two other volcanically produced gases, H_2S and CH_4, were not found at every site and exhibited much lower concentrations, from 0 to 20 mole % H_2S and 0 to 6 mole % CH_4.

Gunn et al. (1982) performed a survey of soil CO_2 concentrations in Waitomo, New Zealand, over 15 months in 1976 - 1977 on volcanic ash soils in dolines. At 20 to 40 cm depths, soil gas CO_2 concentrations ranged from 0.1 to 1.8 vol%. They also found lower concentrations and less variability in autumn through early spring, illustrating the influence of temperature and climatic conditions on concentrations.

Barberi and Carapezza (1994) report soil gas CO_2 fluxes and concentrations for the volcanic island of Thera, Greece, which contains a portion of the Santorini volcano complex. At 50 cm depth, a maximum of 1.5 vol % CO_2 concentration was found, attributed to either carbonate dissolution or from exsolving gas from magma, as no vegetation was present in the study sites.

Those measurements that exceeded 1 standard deviation from the mean were regarded as anomalous, and match closely with known fault systems.

Varley and Armienta (2001) found no volcanic component in the soil CO_2 flux during a survey of a part of the Popocatepetl volcano, Mexico, which was actively erupting and emitting up to 60,000 tons a day of CO_2 in the summit plume. Soil gas CO_2 concentrations in the flux were up to 14 vol %, however isotopic studies indicated that the source of these relatively high concentrations was biological.

On Satsuma-Iwojima volcano, Japan, a 1999 survey found that soil gas CO_2 concentrations varied from 0.03 to 59 vol %, while fluxes ranged from 0.01 to 5,640 g $m^{-2}d^{-1}$ (Shimoike et al. 2002). No trend was found between fluxes and concentrations. Concentrations above 10 vol % generally correlated to areas where the major CO_2 component could be attributed to volcanic sources, as determined by isotopic analyses. In non-volcanic areas, concentrations were less than 5 vol %, but volcanic sources also were found in areas where the CO_2 concentrations were less than 1 vol % (Shimoike et al. 2002).

1.4 Use of soil gas CO_2 fluxes and concentrations to identify fault locations

Measurements of soil gas CO_2 have likewise been used to characterize subsurface structures within geothermal and volcanic areas in numerous studies (e.g. Baubron et al. 2002; Finlayson 1992; Fu et al. 2005; Barberi & Carapezza 1994; Giammanco et al. 1998; Shimoike et al. 2002; Aiuppa et al. 2004).

Delgado-Granados and Villalpando-Cortes (2008) found an 'anomalously high' CO_2 flux of 16.1 g $m^{-2}d^{-1}$ over a fault in the Chichinautzin volcanic field. Five months after the measurement, an earthquake occurred along that fault. They attributed the CO_2 anomaly to degassing from the active fault.

2.0 METHODS AND EQUIPMENT

2.1 Data collection

CO_2 fluxes were measured using a West Systems portable soil flux accumulation chamber (Fig. 2) at each site. The accumulation chamber is a 200 mm diameter open-bottomed vessel, with a battery-powered fan inside to ensure mixing. Flat surfaces were chosen for measurements and the chamber was held down in place by physical means to ensure minimal atmospheric air entered the chamber during measurement. A pump, at a flow rate of 1,000 standard cubic centimeters per minute, introduces soil gas from the chamber to the LICOR 820 instrument (Infrared spectrometer) via tubing with an inline $Mg(ClO_4)_2$ filter to absorb moisture which may cause interference in the reading. Following the original method in Chiodini et al. (1998), CO_2 gas emitting from the soil passes through the chamber and the infrared sensor, it returns to the chamber where it accumulates with the new CO_2 coming from the soil and entering the chamber. The flux is derived by obtaining the increase of the CO_2 concentration with time (ppm-vol s^{-1}). The measurement accuracy of the CO_2 flux measurements method is ±12.5 % (Evans et al. 2001).

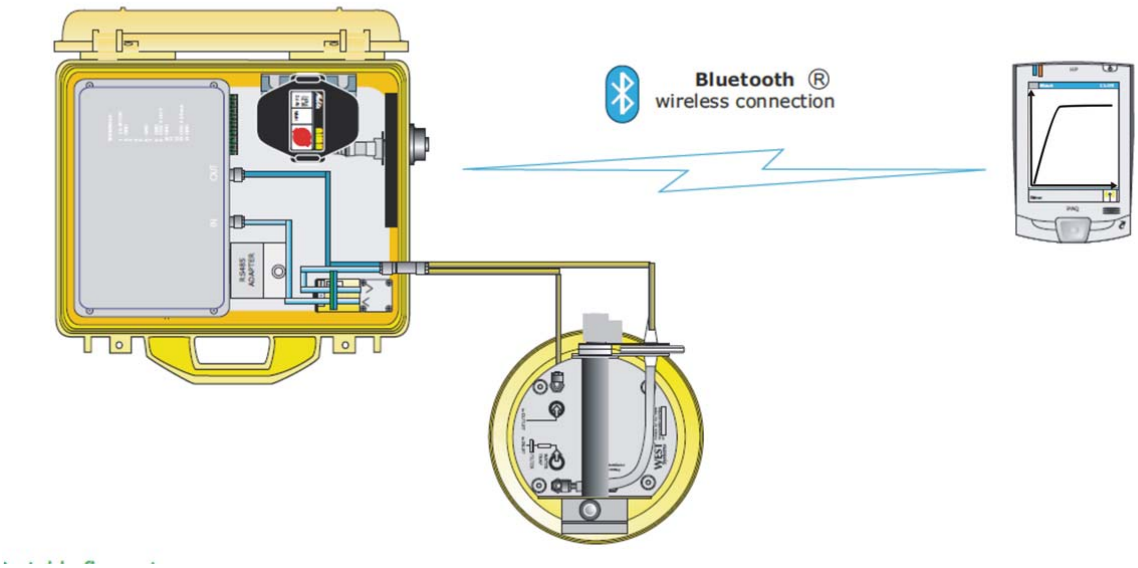

Figure 2. The portable soil gas equipment set up. The orange box is mounted on a backpack frame and contains the LICOR 820 sensor, battery, wireless transmitter and pump. This set up may be used with a soil gas CO_2 probe for CO_2 concentrations as well as the accumulation chamber for CO_2 flux.

Soil gas CO_2 concentration was measured at selected sites by pumping the gas from the soil (25 - 40 cm deep) using a duralumin customized probe with several perforations above a pointed base (Fig. 3). Tubing connected the probe to the LICOR instrument. Soil temperature was recorded at each measurement location, and ambient temperature, pressure and CO_2 concentrations were measured at regular intervals during the study period.

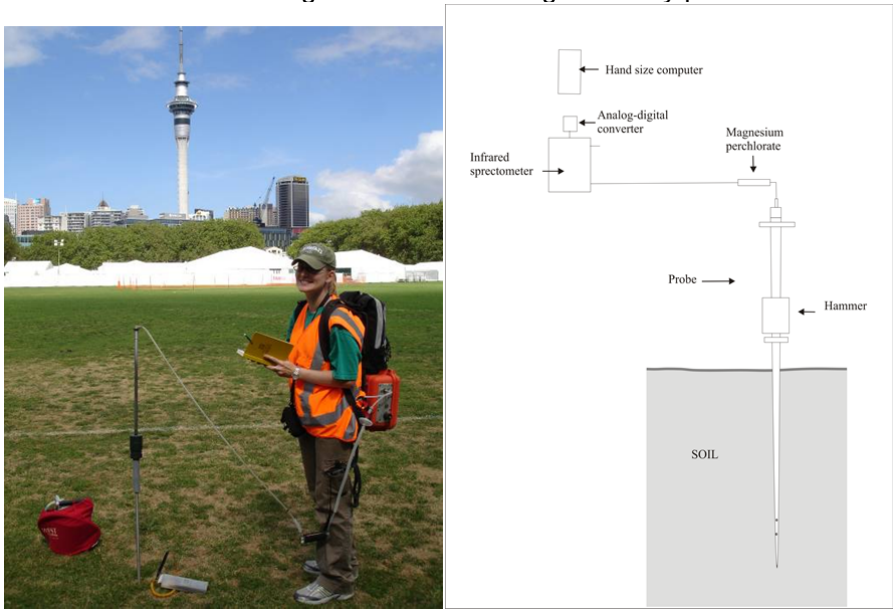

Figure 3. Measurement of soil gas CO_2 concentrations in Victoria Park, Auckland. The perforated probe is inserted into the ground and tubing attached to a $Mg(ClO_4)_2$ water scrubber, then connected to the LICOR sensor, pump, and battery setup in the backpack. The LICOR system was controlled wirelessly using a handheld computer. Soil temperatures were taken at each site (instrument near soil gas probe).

Measurements occurred over a four day period from 16-19 November 2010. Rainfall was minimal during this time; according to NIWA's Mangere and Khyber Pass meteorological station records, on 19 November, 0.5 mm of rainfall was measured at the Khyber Pass station. We did note a period of light drizzle on November 16 from approximately 10:00 am to 10:30 am while taking measurements in Albert Park, but this did not appear to affect our measurements, nor was it recorded by any meteorological stations. Ambient temperatures at these stations ranged from 11.3 °C to 23.6 °C according to NIWA records during the study period.. Recorded ambient temperatures ranged from 17.4 to 25.8 °C while measurements were being taken, while recorded soil temperatures ranged from 14.8 to 34.4 °C. Recorded atmospheric pressure ranged from 1010.7 to 1026.1 hPa.

A total of 443 CO_2 flux measurements were made from the seven sites; additionally, 72 soil gas CO_2 concentration measurements were taken from three sites: Albert Park (site 1), Victoria Park (site 2), and Ihumatao (site 3) (Fig. 4).

Soil gas flux (ppm s^{-1}), as well as atmospheric pressure and temperature, were used in the following equation to calculate daily flux F_{CO2} (g m^{-2} d^{-1}) from each site:

$$F_{CO2} = k\,(V/A)\,(T_0/T)\,(P/P_0)\,(dc/dt),$$

where dc/dt is the change in concentration with time, k is a constant (155.87 m^{-3}), P is the measured pressure (kPa), T is the measured temperature (K), V is the volume of the entire system (0.00624 m^3) and A is the area (0.0314 m^2) of the base of the chamber. Note that T_0 and P_0 normalize the flux to STP (298 K and 101.3 kPa).

Data were compared to their site descriptions to take into account settings which may cause higher than normal fluxes (e.g. over decomposing cut grass or wood chips).

2.2 Site selection

Site selection for this study was very important due to the need for areas spanning the wide range of settings found in Auckland and the varied range of goals for this study. Seven sites were chosen around Auckland (Fig. 4), representing various settings: urban, no fault (1, 2); rural, fault (5, 7); rural, no fault (6); over a suspected volcanic lineament in an urban area (4); over known faults (inferred by geophysics) (5, 7); and at the eastern and western edges of the isthmus (3, 6) to cover prevailing wind from the southwest and non-prevailing winds that occasionally come from the northeast.

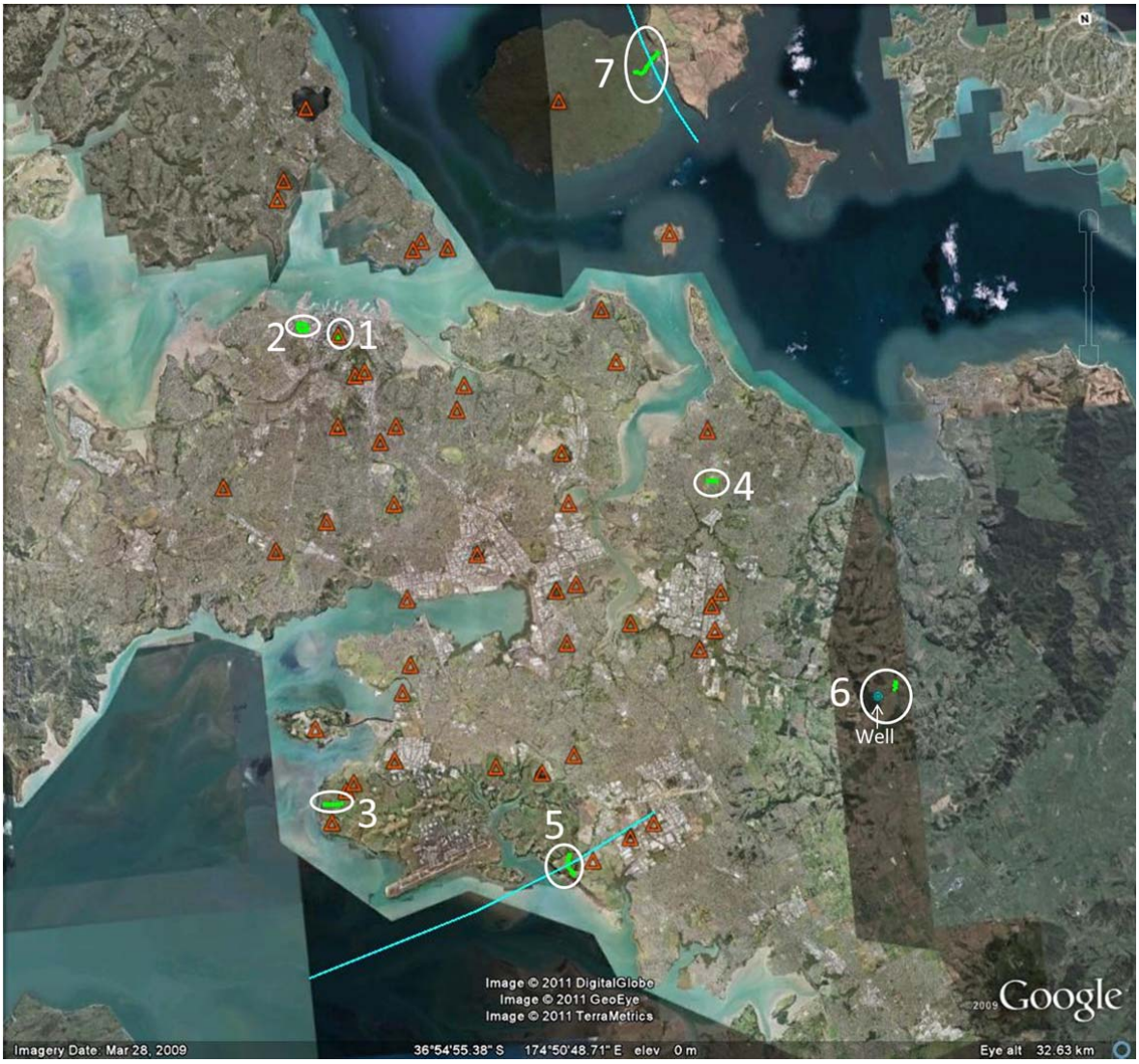

Figure 4. Satellite image of the Auckland Isthmus showing sites selected for the soil gas pilot study. 1-urban, no fault (Albert Park); 2-urban, no fault (Victoria Park); 3-rural, no fault (Ihumatao); 4-urban, fault? volcanic lineament (Lloyd Elsmore Park); 5-rural, fault (Puhunui); 6-rural, fault (Whitford); 7-rural, fault (Rangitoto). Green lines indicate the sampled transect in each area; orange triangles represent AVF vent locations; blue circle indicates the warm water Whitford well; and blue lines indicate faults inferred by geophysical methods and/or borehole information (J. Kenny pers. comm. 2010).

2.2.1 Urban, no fault

Albert Park and Victoria Park (1, 2) were selected as examples of 'urban, no fault' sites for this study (Figs. 4 and 5). Neither overlie suspected faults. Albert Park overlies an AVF volcano and Victoria Park has no volcanic history. Both are located near busy streets or motorways and have been modified extensively in the past 150 years.

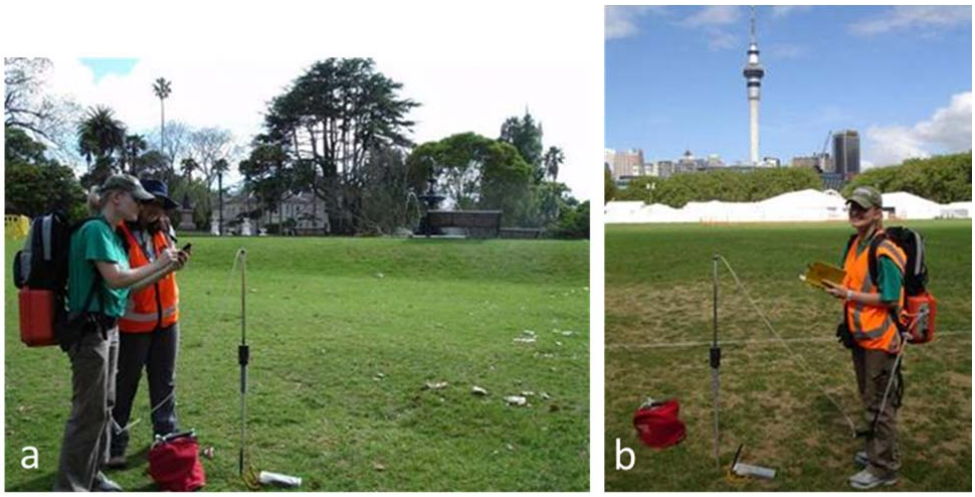

Figure 5. Measuring soil gas CO_2 concentrations and fluxes in a) Albert Park and b) Victoria Park, two urban, no fault settings in Auckland. Soil gas fluxes were also taken at these locations.

2.2.2 Rural, no fault

The Ihumatao site (3) is located in the far western portion of Auckland in a rural setting (Figs. 4 and 6). The airport is located to the southeast. No faults are known in this area.

Figure 6. Measuring soil gas CO_2 fluxes in Ihumatao, a rural, no fault setting in the AVF. Soil gas concentrations were also taken.

2.2.3 Urban, fault

Lloyd Elsmore Park (4) is located in East Tamaki, a heavily industrialized area in eastern Auckland (Figs. 4 and 7). A fault, suspected from geophysical methods, may run underneath this park; there is also a suspected volcanic lineament comprised of four volcanic vents south of this site. Warm water has been found in wells in this area, indicating a possible fracture (http://www.arc.govt.nz/albany/fms/main/Documents/Environment/Water/W02%20Geothermal%20water.pdf).

Figure 7. Measuring soil gas CO_2 fluxes in Lloyd Elsmore Park, Auckland, an urban area overlying a suspected fault, a possible fracture connecting warm water to the surface, and a potential volcanic lineament. Soil gas concentrations were not measured at this site.

2.2.4 Rural, fault

Puhunui Reserve (5), Whitford (6) and Rangitoto (7) were selected to fulfil the rural, fault settings of the study (Figs. 4 and 8). The Wiri Fault is known to run through Puhunui Reserve from geophysical methods, and Whitford has been the study of numerous geothermal investigations due to the hot water in bores found in this area (Bromley et al. 2006). The Whitford study area included measurements around a 198 m deep artesian well with a maximum temperature of 60.5 °C. The Islington Bay Fault, inferred by geophysics to comprise the far eastern limit of the AVF, runs under the eastern part of Rangitoto Volcano, near the Motutapu Island causeway.

Figure 8. Measuring soil gas CO_2 flux measurements in a) Puhunui Reserve (5), b) next to a warm water well in Whitford (6), and c) on Rangitoto Volcano (7). These sites represented rural, fault areas in the study. Soil gas concentrations were not measured at these sites due to time and pedology constraints.

3.0 RESULTS AND DISCUSSION

3.1 Flux

Soil gas CO_2 fluxes in the Auckland area ranged from 0 to 108.7 g $m^{-2}d^{-1}$, with an average flux of 26.6 g $m^{-2}d^{-1}$across all sites (Table 1).

Table 1. Soil gas CO_2 flux ranges as found in various settings in the AVF in November 2010.

Setting	Minimum Flux (g $m^{-2}d^{-1}$)	Maximum Flux (g $m^{-2}d^{-1}$)
Urban, No fault	2.78	90.33
Rural, No fault	0.84	63.98
Urban, Fault	0	101.6
Rural, Fault	0	108.68

Urban vs rural and fault vs no fault areas are each statistically different at a 95% confidence interval using a heteroscedastic 2 tail t-test. Further study is necessary to glean the causes of these differences, especially considering the rural, no fault sample pool is comparatively very small.

3.1.1 Probability distribution of the CO_2 flux

The computation of the CO_2 flux data, based on a graphical statistical approach (GSA) (Chiodini et al. 1998, 2001; Cardellini et al. 2003), permits the differentiation among different degassing mechanisms of CO_2. The GSA consists of the partitioning of CO_2 flux data into different log-normal populations. The proportion, the mean and the standard deviation of each population are estimated following the procedure introduced by Sinclair (1974). For the sampling period in this study, the distribution of CO_2 fluxes (F_{CO2} values in g m^{-2} d^{-1}) identifies two populations of data (Fig. 9): a high CO_2 population (A in Fig. 9b) corresponding to 67% of the data, and a low CO_2 population (B in Fig. 9b) corresponding to the 33% of F_{CO2}. The two-population percentages were checked and validated by combining both populations in the proportion of 67% A and 33% B at various levels of log F_{CO2}. The checking procedure uses the following relationship:

$$P_M = f_A P_A + f_B P_B,$$

where P_M is the probability of the "mixture"; P_A and P_B are cumulative probabilities of population A and B from the plot of Fig. 9b at a specified x value; and f_A and f_B are the proportions of populations A and B. In Fig. 9b, the points of the "mixture" are represented by grey triangles. Afterwards, parameters of the individual partitioned populations can be estimated. To estimate the arithmetic mean value of CO_2 flux and the central 95% confidence interval of the mean in the original data units (in g $m^{-2}d^{-1}$) for each population, the Sichel's t estimator (David 1977), following Chiodini et al. (1998), was used. The population A mean flux values were estimated as 35 g m^{-2} d^{-1} (95% confidence interval of the mean 33 - 37 g m^{-2} d^{-1}). Population B has a mean value of F_{CO2} = 12 g m^{-2} d^{-1} (95 % confidence interval of the mean 10 - 15 g m^{-2} d^{-1}).

Populations A and B, representing low CO_2 flux measured at all the sites of study, suggest that they both represent background levels, mainly controlled by biological CO_2 production in the soil. The difference between population A and B depends only on the permeability of the soil. For example, Rangitoto Island is covered by low permeability lava flows and the CO_2 flux measured was for the most part relatively low (Fig. 18).

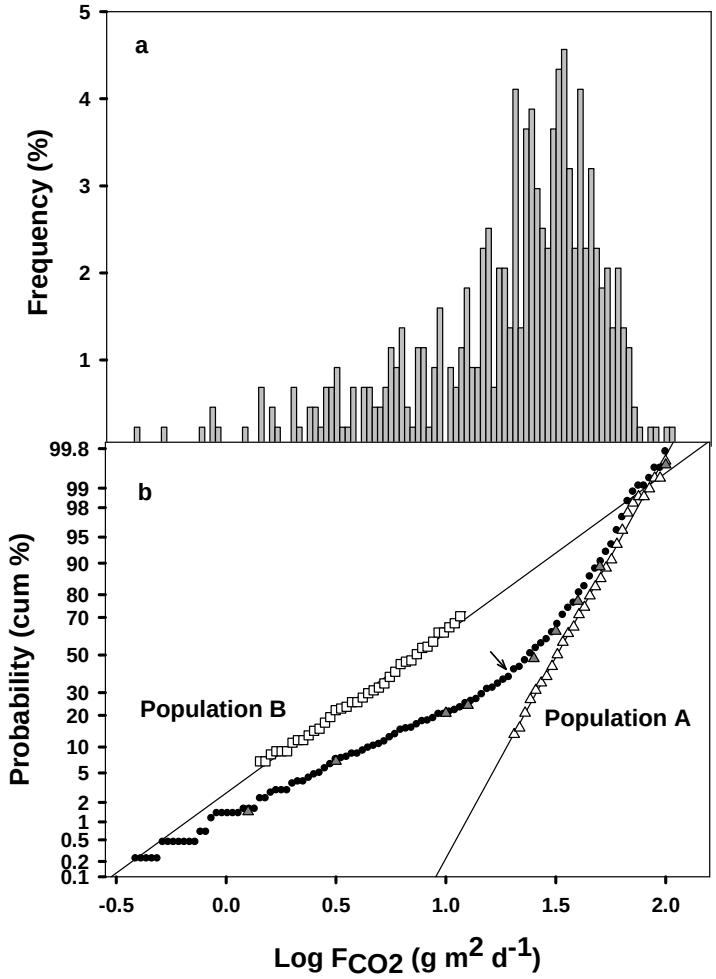

Figure 9. Histogram (a) and probability plot (b) of CO_2 flux data (black circles). Populations A (open triangles up) and B (open squares) are shown as straight lines. The inflection point is indicated by an arrow and corresponds to 67% of population A and 33% of population B.

3.2 Soil CO_2 concentration

Overall, soil gas CO_2 concentrations ranged from 393 to 10,140 ppm. Soil gas CO_2 concentrations at specific sites are as follows: 407 ppm to 10,140 ppm in Albert Park (1; urban, no fault); 397 to 8,590 ppm in Victoria Park (2; urban, no fault); 410 to 7,030 ppm at Ihumatao (3; rural, no fault). No soil gas CO_2 concentrations were taken at any other site due to time constraints and the compacted nature of the soil.

The 72 measurements were insufficient to allow a computation using the GSA procedure; the data was too sparse for meaningful analysis on the probability graph.

3.3 Soil temperature

3.3.1 Probability distribution of the soil temperature

Soil temperatures measured at 10 cm depth ranged from 14.8 to 34.4 ^{o}C. Using the GSA method, the distribution of the soil temperature indicates three populations of data (Fig. 10). On the plot we can identify relatively high temperatures (Population A in Fig. 10b) corresponding to 3 % of the data, average temperatures (Population B in Fig. 10b) corresponding to 61 % of temperature, and a lower temperature range (Population C in Fig. 10b) corresponding to 36 % of the data. The three-population percentages were checked and validated by combining the three populations in the proportion of 3% A, 61 % B and 3% C at various levels of log

Temperature. The population A mean temperature values were estimated as 26.6 ^{o}C (95 % confidence interval of the mean 26.2 - 27.4 ^{o}C). Population B has a mean value of temperature = 22.6 ^{o}C (95 % confidence interval of the mean 22.5 - 22.7 ^{o}C). The population C mean temperature values were estimated as 18.2 ^{o}C (95% confidence interval of the mean 18.1 - 18.3 ^{o}C). Population B and C represent atmospheric temperatures that corroborate the range of temperature varying from 11.3 to 23.6 ^{o}C, according to NIWA records during the study period. Low soil temperatures, representing by population C, were measured in the morning or below the trees (shade areas). Mid-range temperatures, represented by population B, were measured in the afternoon or on lawns. The highest temperatures, represented by population A, could be due to higher decomposition in the soil or in areas where vegetation cover is sparse or almost non-existent and therefore more sensitive to the heat from the sun.

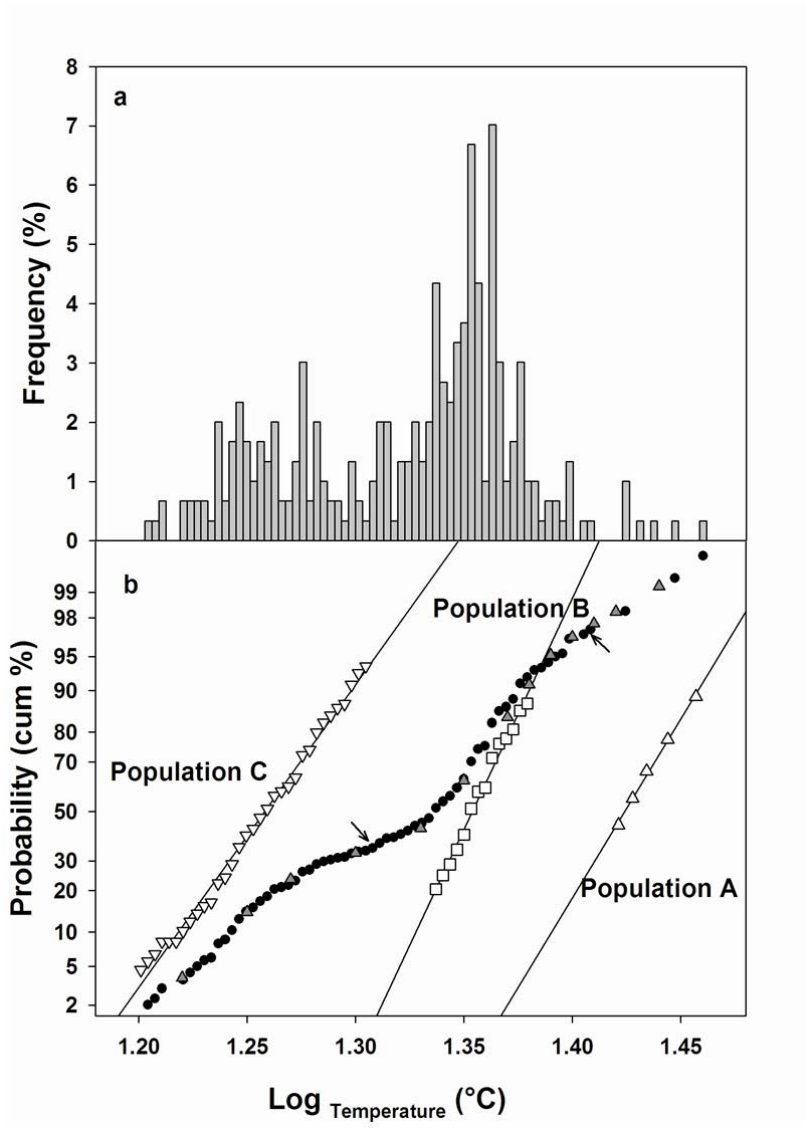

Figure 10. Histogram (a) and probability plot (b) of temperature data (black circles). Populations A (open triangles up), B (open squares) and C (open triangles down) are shown as straight lines. The inflection point is indicated by an arrow and corresponds to 3 % of population A, 61 % of population B and 36 % of population C.

3.4 CO_2 flux, soil CO_2 concentration and soil temperature maps

CO_2 fluxes and soil temperatures were classified using the results from the GSA method, while soil CO_2 concentrations were classified using equal intervals, as there were not enough data to use the GSA method. Classifications were then plotted on a Google Earth map for each site.

3.4.1 Urban, no fault

The CO_2 flux and soil CO_2 concentration map for Site 1 (Albert Park) is shown on Figure 11a. One measurement site exhibited a CO_2 flux higher than 75 g $m^{-2}d^{-1}$ and a soil CO_2 concentration higher than 6,896 ppm (red spot on figure). This suggests a high production of CO_2 in the soil but also a high diffusivity/permeability dominated by advective gas transport at this spot. The high CO_2 flux is likely due to high rate of decomposition relatively common in urban areas (Lorenz and Lal 2009). CO_2 fluxes measured in Chicago (USA) were on average 38 g $m^{-2}d^{-1}$ with the highest flux at 144 $gm^{-2}d^{-1}$ (Grimmond et al. 2002). Albert Park also overlies a labyrinth of underground tunnels which may affect the distribution and channeling of CO_2 in the subsurface. The soil temperature was likely be controlled only by the atmospheric temperature (Fig. 11b).

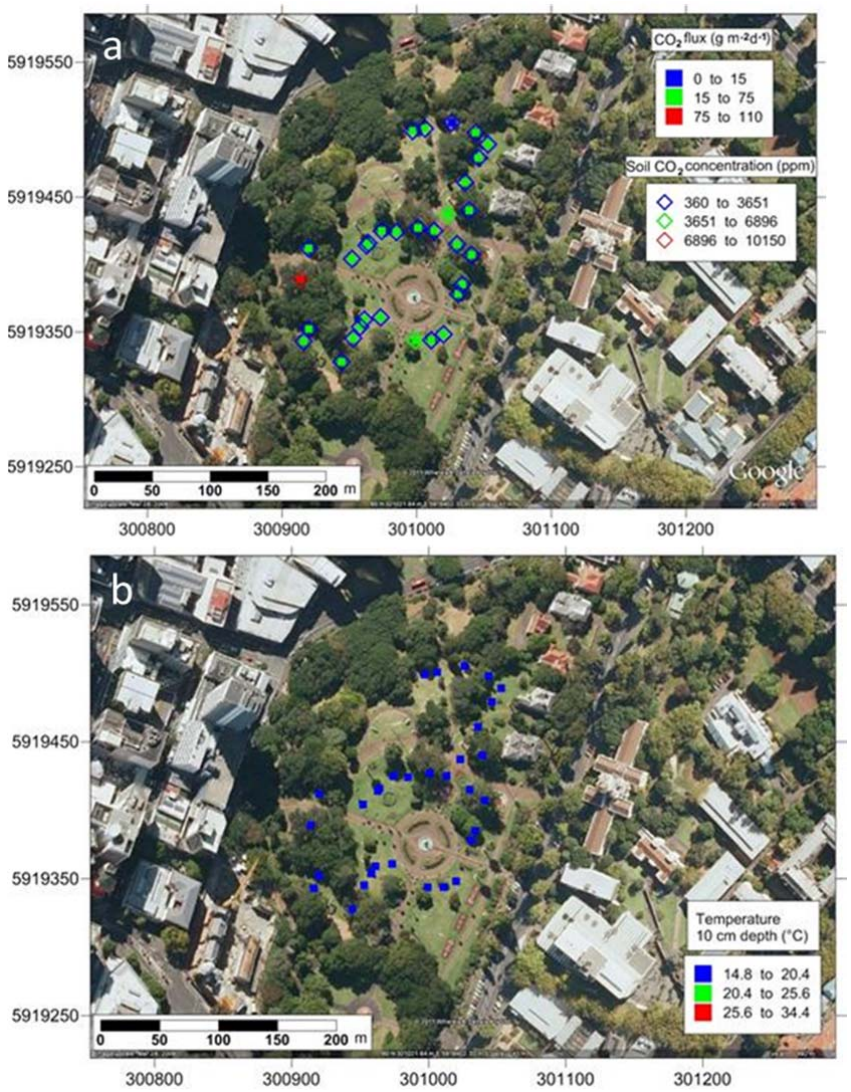

Figure 11. Site 1 (Albert Park) measurements: a) CO_2 fluxes and soil CO_2 concentration and b) soil temperature at 10 cm depth.

The CO_2 flux and soil CO_2 concentration map at Site 2 (Victoria Park) is shown on Figure 12a. The measured CO_2 flux showed a negative correlation with the soil CO_2 concentration. This suggests that this zone was dominated by diffusive gas transport depending greatly on the permeability of the soil. In urban parks, high levels of atmospheric CO_2 have been observed in soils (Groffman and Pouyat 2009). These levels of soil CO_2 concentration (> 6896 ppm) at Sites 1 and 2 (Albert and Victoria Parks) are likely to be the result of elevated levels of atmospheric CO_2 during peak traffic hours.

The soil temperature at Victoria Park is shown in Figure 12b. The temperature was lower than 20.4 ^{o}C below the trees (shade areas) and higher than 20.4 ^{o}C on the grass, showing that the soil temperature was only dependent on the individual characteristics of each measurement site.

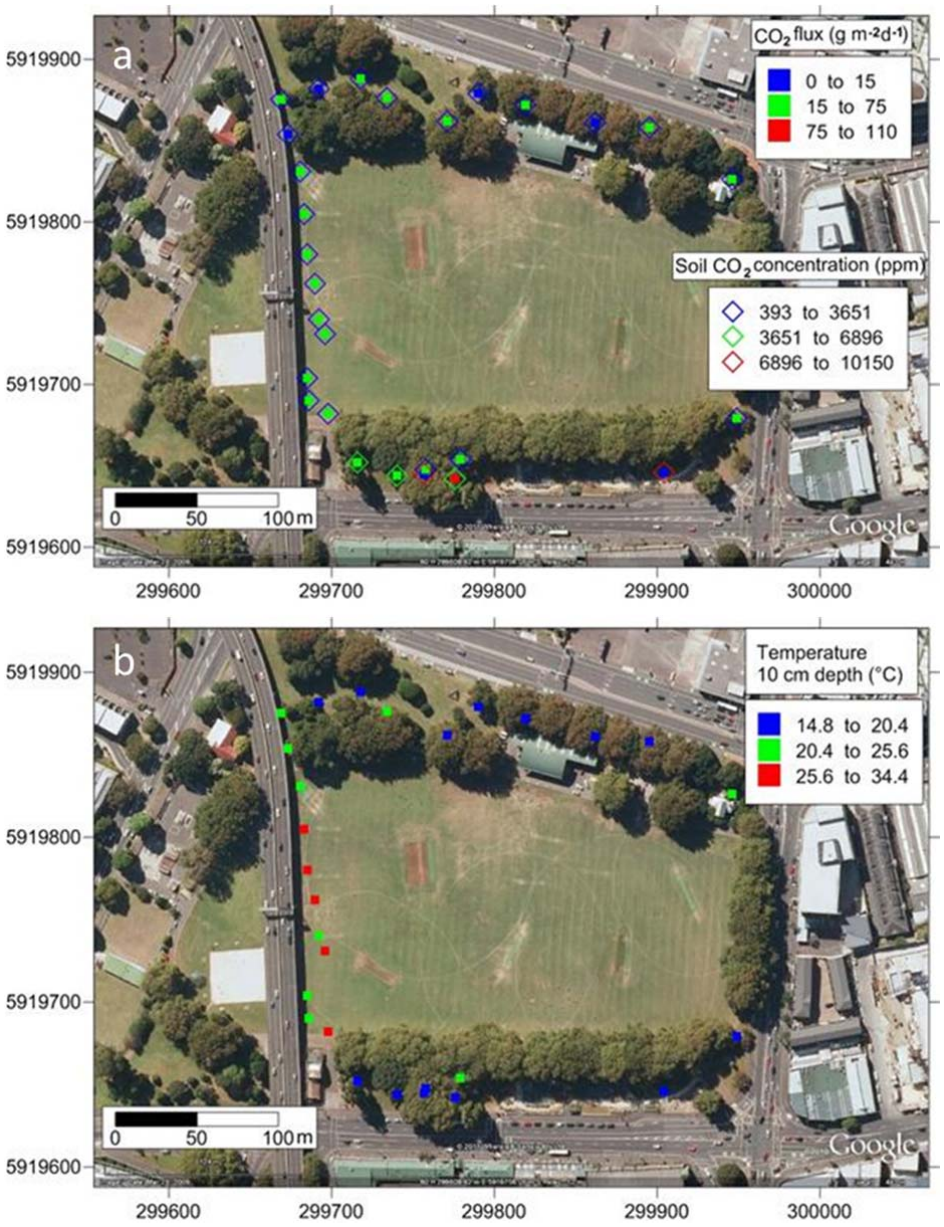

Figure 12. Site 2 (Victoria Park) measurements: a) CO_2 fluxes and soil CO_2 concentration and b) soil temperature at 10 cm depth.

3.4.2 Rural, no fault

At Site 3 (Ihumatao), CO_2 flux values are below 75 g $m^{-2}d^{-1}$ and soil CO_2 concentrations show a wide range of values (up to 9,846 ppm). The fluxes are quite similar to those measured at urban areas, although located in a rural area. There is no relation between CO_2 flux and soil CO_2 concentration. The temperature shows no anomaly with values ranging from 14.8 to 20.4 ^{o}C.

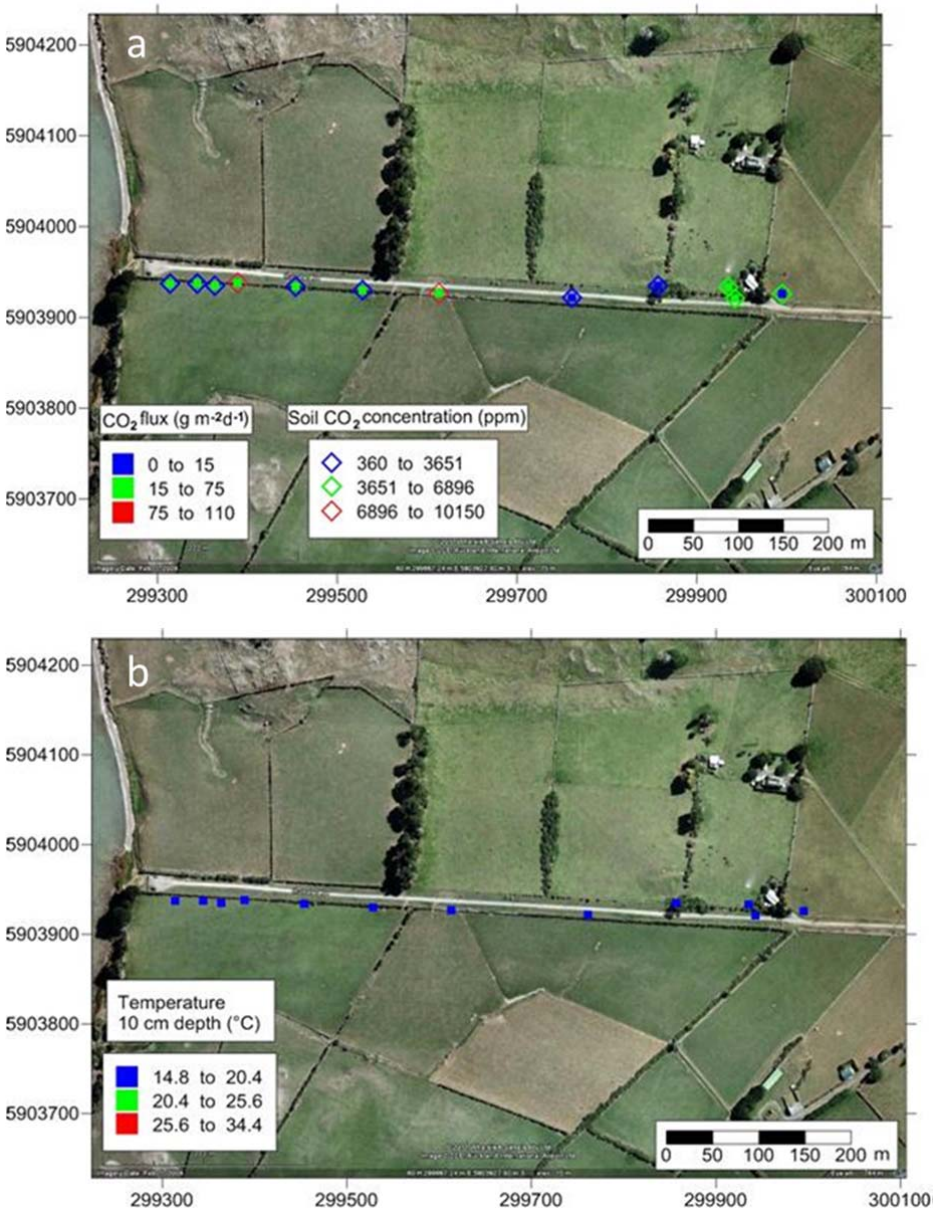

Figure 13. Site 3 (Ihumatao) measurements: a) CO_2 fluxes and soil CO_2 concentration and b) soil temperature at 10 cm depth.

3.4.3 Urban, fault

Along the transect performed at Site 4 (Lloyd Elsmore Park), one high CO_2 flux reading (102 g $m^{-2}d^{-1}$) was measured but was not correlated with a high temperature (Fig. 14a). The soil temperature map shows high soil temperature common in urban lawns (Fig. 14b).

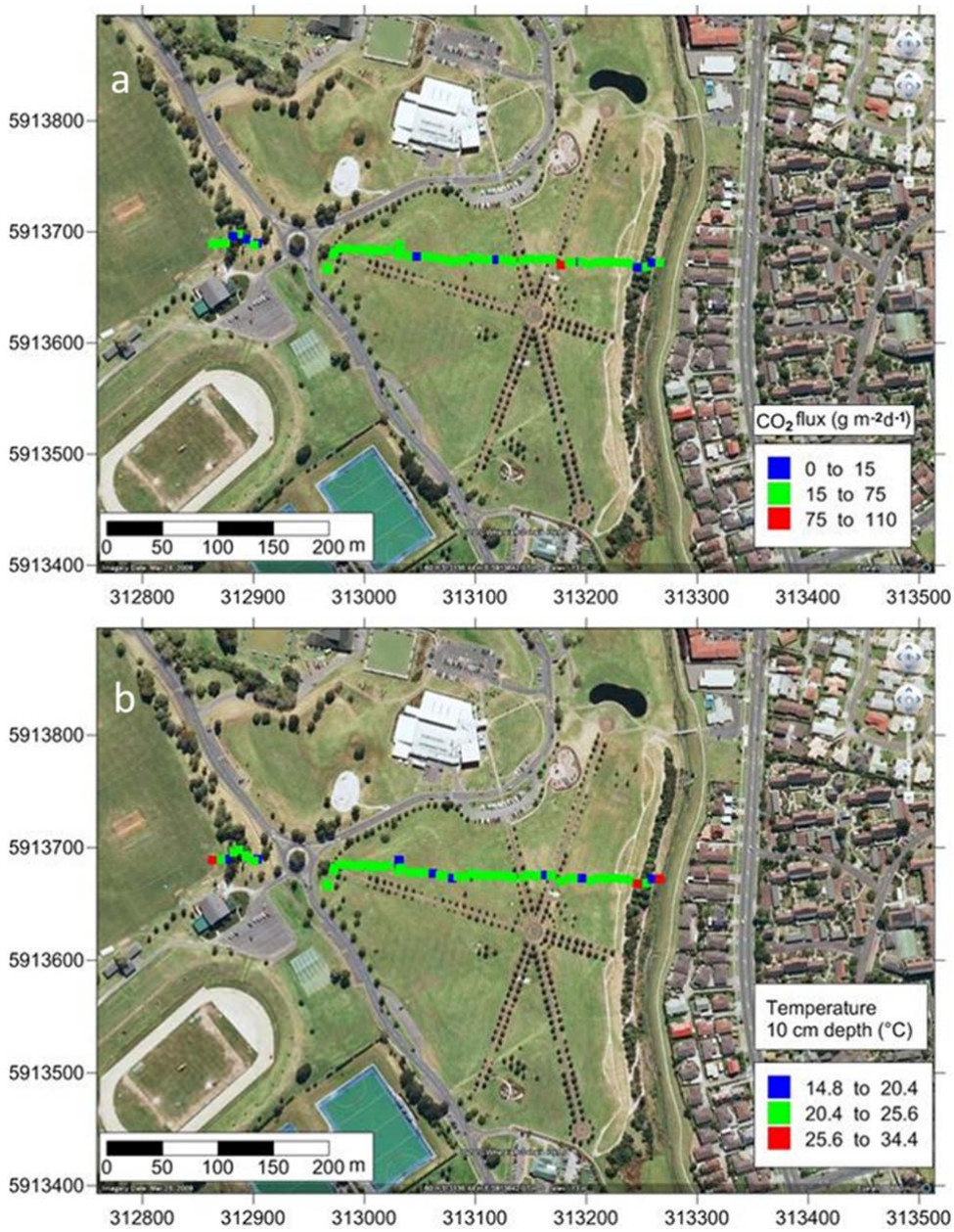

Figure 14. Site 4 (Lloyd Elsmore Park) measurements: a) CO_2 fluxes and b) soil temperature at 10 cm depth.

3.4.3 Rural, fault

3.4.3.1 Puhunui and Whitford

CO_2 fluxes measured at Sites 5 and 6 (Puhunui Reserve (Fig. 15) and Whitford (Fig. 16)) showed no anomalous values.

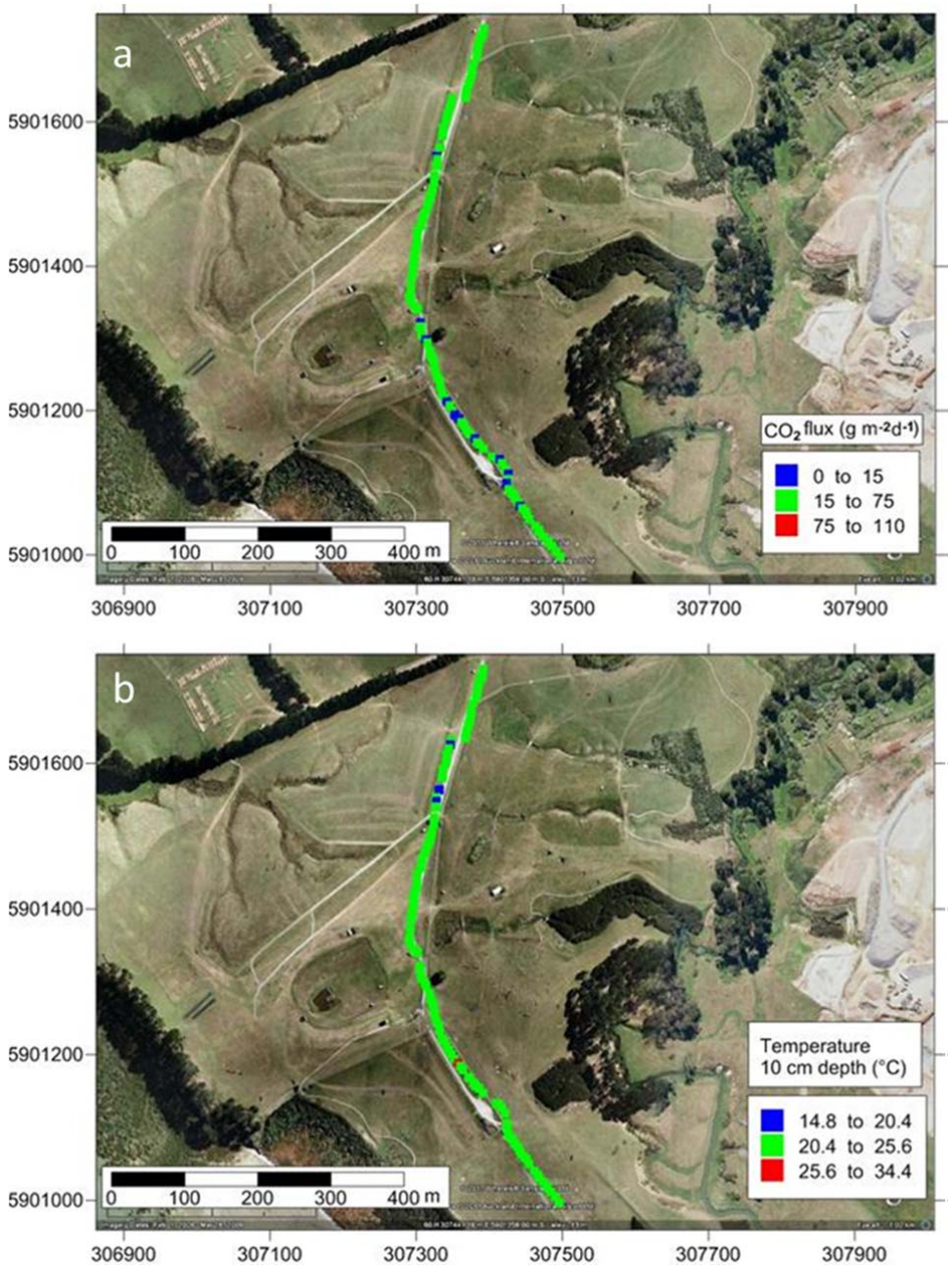

Figure 15. Site 5 (Puhunui Reserve) measurements: a) CO_2 fluxes and b) soil temperature at 10 cm depth.

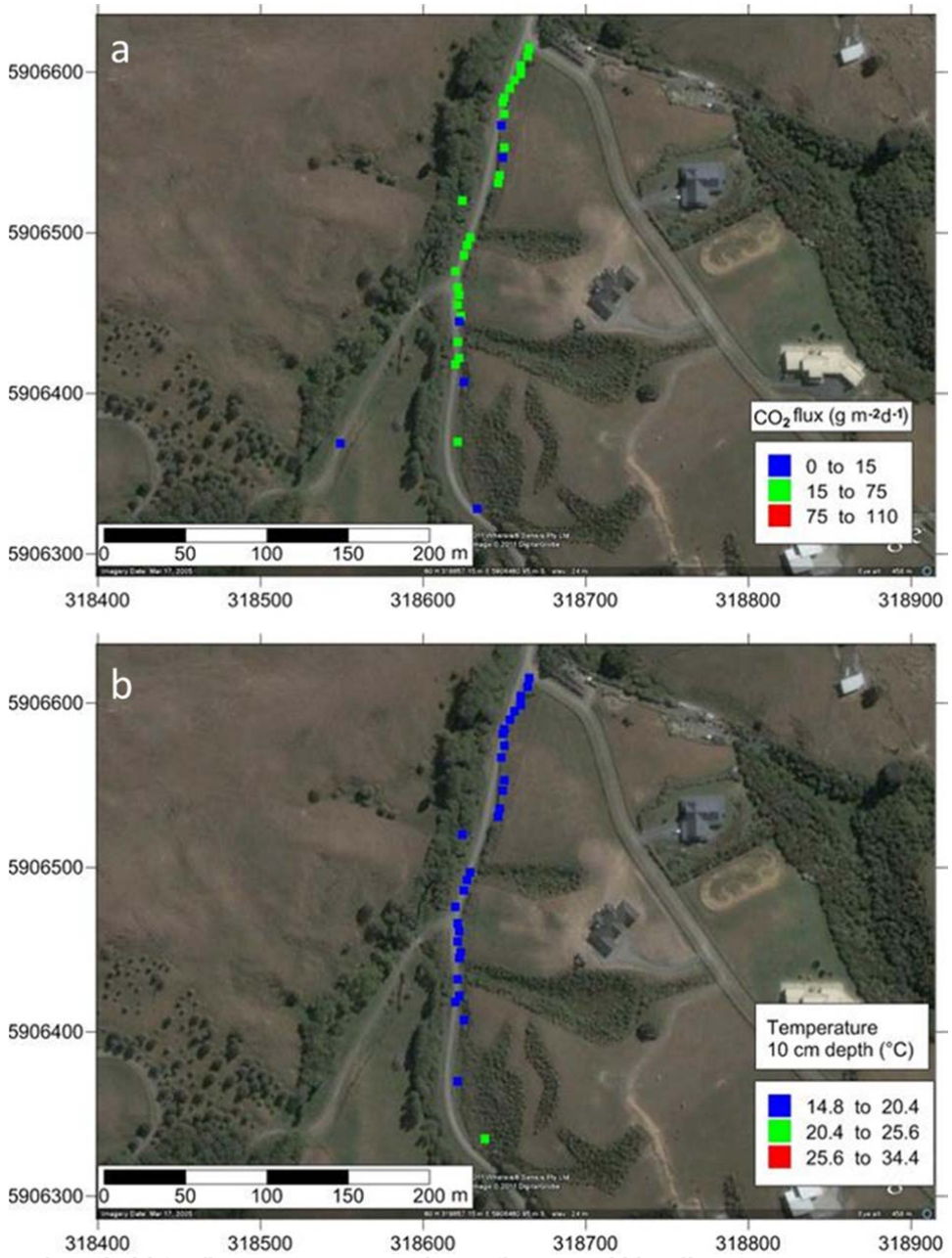

Figure 16. Site 6 (Whitford) measurements: a) CO_2 fluxes and b) soil temperature at 10 cm depth.

Some CO_2 flux measurements were performed around a 198 m deep well at Site 6 (Whitford) containing ~60 ^oC water (black circle on Fig. 17). The highest point measured was west of the well (109 g $m^{-2}d^{-1}$).

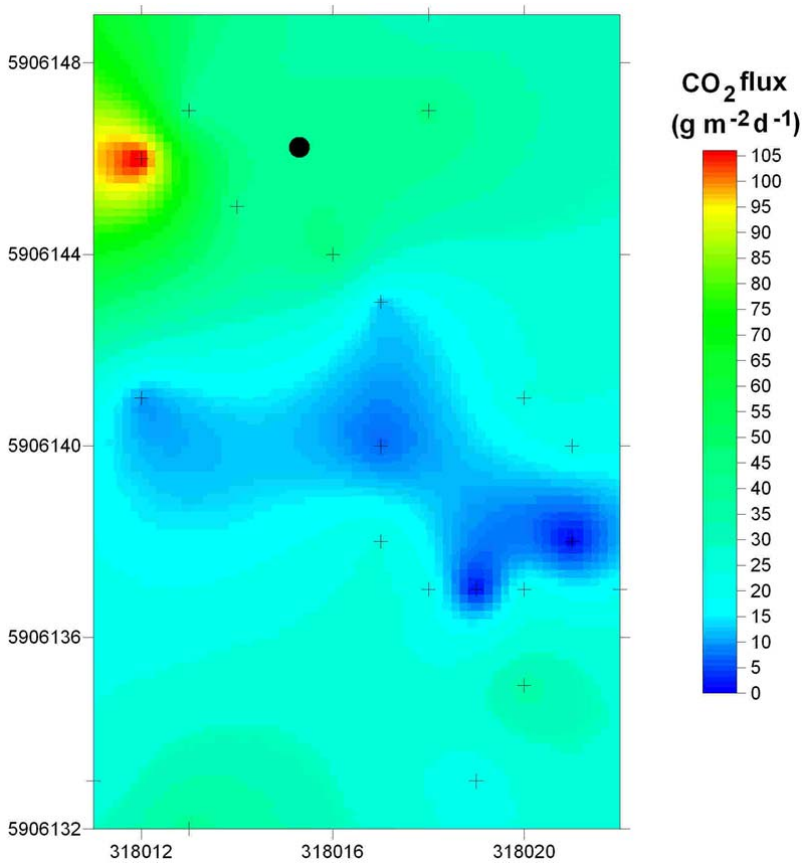

Figure 17. CO_2 flux map around the Whitford well at Site 6. The black point is the site of the well. The measurement locations are represented by crosses.

3.4.3.2 Rangitoto

The majority of the CO_2 fluxes measured on lava flows at Site 7 (Rangitoto Island) were quite low (not more than 64 g $m^{-2}d^{-1}$; Fig. 18). There was no trace of the suspected fault in the transect. It is postulated that the low permeability of the lava flows prevent the CO_2 from escaping to the surface.

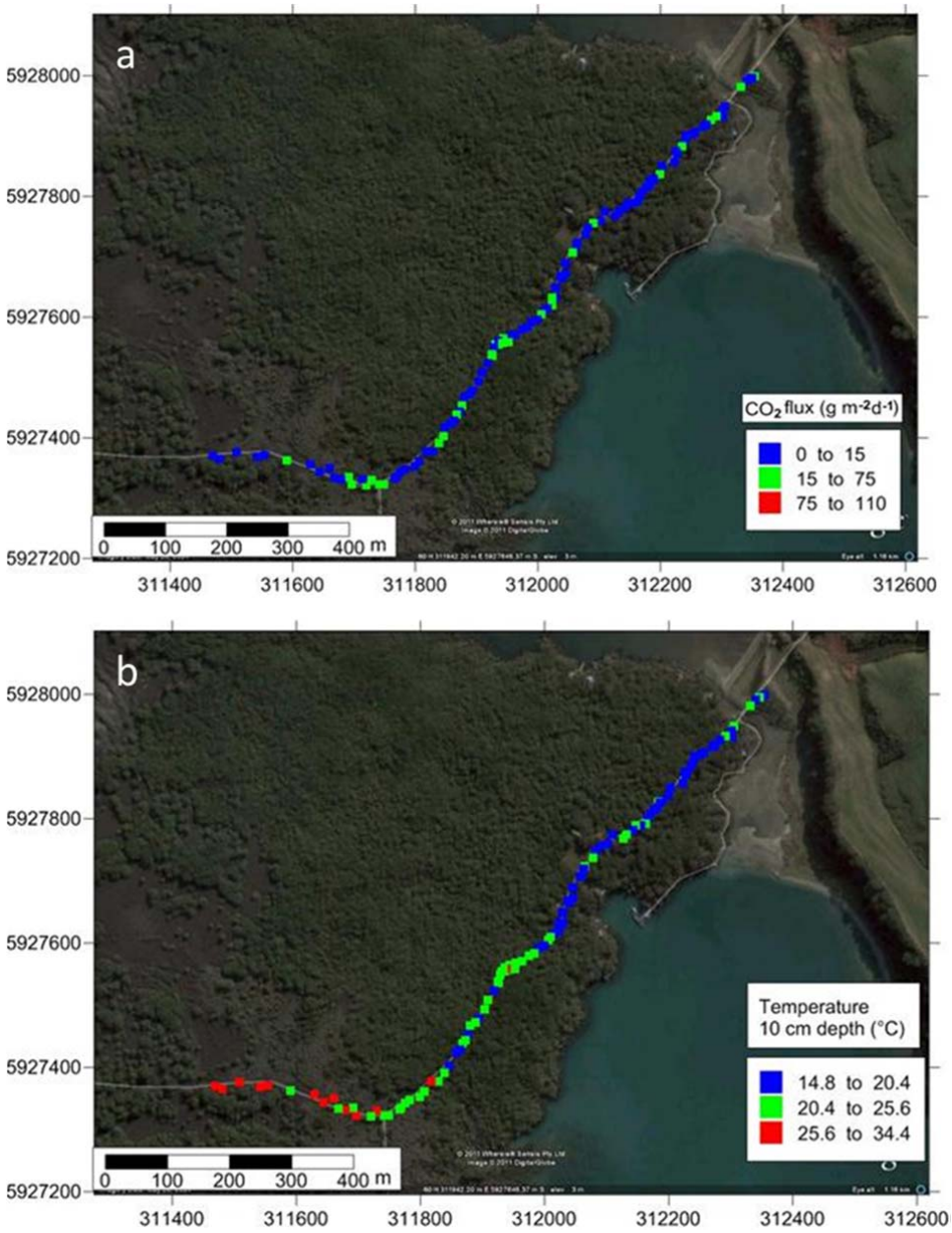

Figure 18. Site 7 (Rangitoto Island) measurements: a) CO_2 flux and b) soil temperature at 10 cm depth.

4.0 CONCLUSIONS

In summary, comparison of CO_2 flux, soil CO_2 concentration and soil temperature studies in urban vs non-urban areas with no fault showed that higher CO_2 fluxes and soil CO_2 concentrations were measured in urban areas. This suggests that high levels of atmospheric CO_2 increases the soil CO_2 concentration, due to the higher CO_2 consumption by the soil and/or the high rate of decomposition in urban areas.

The CO_2 flux and soil temperature studies in urban and non-urban areas with inferred faults showed that natural background CO_2 flux was measured at all the areas and quite low CO_2 flux was observed at Rangitoto Island due to the low permeability of the lava flows. This suggests that the faults were not found in the area of study; they could be present at depth but were not open conduits for transport of deep degassing.

Based on this pilot study, soil gas CO_2 concentration and flux baselines for the AVF are typical of those produced by biogenic sources and for New Zealand. No volcanic component seems to be present at this time, although isotopic analyses were not performed, therefore this cannot be confirmed categorically. Concentrations in fault areas are statistically different from those in no fault areas, although the cause could be site-specific conditions rather than the presence of faults, as no obvious anomalies were encountered on any transects across suspected or known faults. It is also interesting to note that urban and rural areas are statistically different, perhaps reflecting a greater influx of atmospheric CO_2 into the soil in urban areas and illustrating the varied influence of site conditions.

5.0 FUTURE WORK & RECOMMENDATIONS

The results of this study, although largely inconclusive, do hint at possible interesting variations in soil CO_2 across Auckland. Future work to expand the areas studied and to gather more fluxes are necessary to determine the extent and reasons for the variations. Transects in more well-known fault areas may refine the results. Seasonal variations and trends may become apparent through measuring at each site over a year, and over various timeframes.

Pollution monitoring in Auckland takes place at 14 sites around Auckland. Atmospheric CO_2 is not measured in Auckland, but SO_2 is monitored from 3 locations, all in the industrial Penrose suburb of Auckland. SO_2 has been monitored since 1975 and has been 'low' at less than 10 micrograms per cubic meter since 2001. (http://www.arc.govt.nz/albany/app_templates/behaviours/ARCpopupImage.cfm?file_uuid=824451F4-14C2-3D2D-B9CC-003B649385B5&caption=SO2%20Annual%20Averages).

Other gases monitored in Auckland include ozone, NO_2, O_3, CO, and fine particles (http://www.arc.govt.nz/albany/fms/main/Documents/Plans/Technical%20publications/251-300/TP296%20Ambient%20air%20quality%20monitoring%20network.pdf).

Future work could include collaborating with the Auckland Council, which monitors atmospheric pollution in Auckland. A tentative plan for the Auckland Council to monitor atmospheric CO_2 in Auckland is being formulated. New equipment being procured for this monitoring will also be convertible for soil gas CO_2 monitoring in the event of an emergency where more localized data collection is necessary, such as in the case of suspected eruption. Having the council flag any anomalous measurements of SO_2 and CO_2 for a volcanologists' review could be helpful to put into practice.

Expanding this study with SO_2, Rn and He monitoring or baselines (CO_2 acts as a carrier for Rn and He) could also be helpful (e.g. Fu et al. 2005; Baubron et al. 2002; Granieri et al. 2003). Analyzing isotopes in the field would help quickly identify volcanic vs biogenic vs anthropogenic sources (Cerling et al. 1991; Takahashi et al. 2004).

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