CO_2 FLUXES FROM GEOTHERMAL SYSTEMS: ASSESSING THE EFFECTS OF EXPLOITATION, AND THE CARBON TAX IMPLICATIONS

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SUMMARY – The total flow of CO_2 from geothermal systems to the atmosphere has rarely been measured, and probably never directly assessed. The natural fluxes from fields need to be measured, or otherwise assessed, and the effects of exploitation on these fluxes quantified, if fair and defensible carbon tax liabilities are to be imposed. The exploitation of geothermal energy releases greenhouse gases and causes disturbances to the natural flows, but these need to be quantified, both during the term of the exploitation and in the longer term. In 1992, attempts were made to measure the flows from three sites above geothermal systems in the Taupo Volcanic Zone. The data obtained gives important information on the range of fluxes at different sites, and on the variability of the flows in response to atmospheric variables and biological activity in the soils. The range of fluxes ascribable to geothermal CO_2 emissions ranged from 0.5 to 3 g/m^2 at Wairakei and Tauhara and up to 15-25 g/m^2 at a hot site Reporoa. These values are higher than has been obtained elsewhere. The implications of these measurements and observed changes in heat and steam fluxes from exploited geothermal systems are that the induced increase in greenhouse gas releases to the atmosphere is very much underestimated.

1. INTRODUCTION

The assessment of the flows of CO_2 to and from the atmosphere is very topical as a consequence of the concerns about greenhouse gas accumulation in the atmosphere, and the fiscal measures which are proposed to discourage such discharges. The dominant fluids in geothermal systems are water (95-99%) and carbon dioxide (up to 5% by weight): Methane is found in concentrations up to 0.05% by weight.

Assessments of the contributions of CO_2 to the atmosphere from geothermal systems have been made (Kerrick *et al.*, 1995, Seward and Kerrick, 1996) on the basis of heat flows and deep geothermal fluid compositions. They used two geothermal regions (Taupo Volcanic Zone, New Zealand, and the Salton Trough, California, U.S.A.) as the basis for extrapolating over the entire earth. They estimated that the TVZ contributes 10^{10} mol/a. Such an approach might be expected to be able only to give a maximum value for the flux, since a number of mechanisms may change the quantity of the gas which reaches the surface. Such mechanisms would include reversible reactions such as mineralisation (e.g. calcite formation in veins), dissolution in groundwaters, direct fixing in vegetation and soils, and dissolution in surface waters, especially ocean waters.

The Climate Change Response Bill currently before the New Zealand Parliament uses the Kyoto Protocol definition which covers "human-induced greenhouse gas emissions" from various sources. The definition does not explicitly mention geothermal systems but does have the "other" category into which geothermal emissions would presumably fall. The Bill requires that the Government "improve its national inventory system" subject to sufficient numbers of countries ratifying the protocol. However, the Government will be taking the power to compel the provision of information and to enter property to carry out tests and sampling, with penalties for non-compliance. In other words, the Government expects users of geothermal energy to provide them with the information necessary to compile the inventory, or it will estimate it itself.

For this reason it would seem wise for the geothermal power generating companies to quantify current and long-term variations in CO_2 discharged to the atmosphere, as well as to have some mechanism for assessing the natural or pre-existing flux and its variability.

A crude representation of current attitudes might be:

- The quantities of greenhouse gases being discharged are minimal, especially when compared with conventional thermal power plants, so there is not an issue.
- The CO_2 being produced is "natural", would be produced anyway, and so no new CO_2 is being added to the environment.
- Only the CO_2 being discharged from the power plant condenser stacks is significant.

- The CO_2 being produced as a result of exploitation is the same as would be produced naturally, on the same time-scale.

None of these assumptions is likely to be true, so assessment is required of the magnitude (and hence significance) of short-term increased CO_2 fluxes that result from the exploitation of geothermal fluid. These fluxes will be both from production and from the increased (or decreased) gas flow to the ground surface. Increased flows of heat and steam to the surface are seen in many exploited geothermal systems where a steam zone is created in permeable lithologies.

Better knowledge of the long-term variability of gas discharges from geothermal systems, both pre- and post-exploitation is required and this in turn requires a much better understanding of the various sources and sinks of geothermal CO_2, the various reservoirs, flow paths, mass balance and the effects of perturbations.

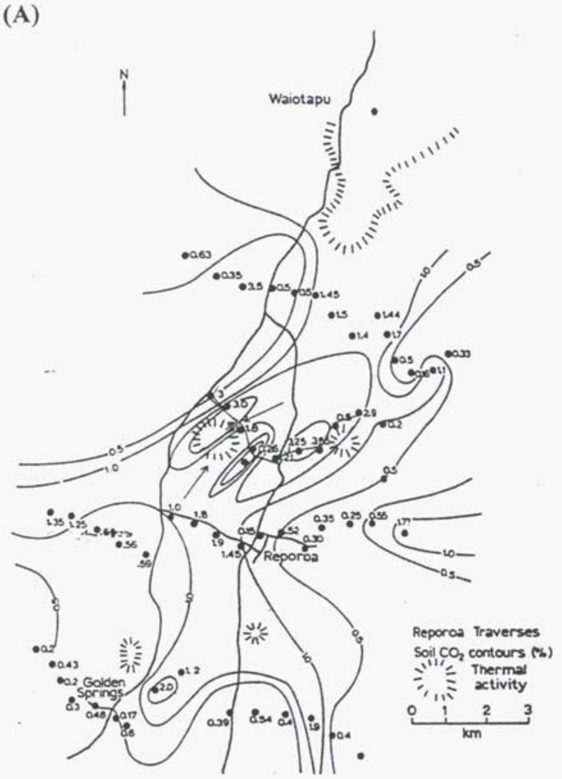
1.1 Measurement of CO_2 flux

The measurement of the flow of gaseous CO_2 from the earth's surface is not simple. There are two basic measurement techniques; atmospheric and discrete. The most technically sophisticated uses laser infra-red beams to measure adsorption due to CO_2 in the airspace above the region to be assessed, but other methods using towers with multiple sampling points at different heights are commonly used. Atmospheric profile monitoring is essential, along with complex mathematical modelling of the data.

The discrete site techniques consist of making measurements at a number of sites, and integrating these measurements to derive an estimate of the flux over an area. The technique suffers from uncertainties due to inhomogeneities in the diffusive characteristics of the area, as well as problems with the effects of the measurement technique itself on the fluxes. Interference from CO_2 produced by soil biota and plants is a factor in both methods. The effects of soil biota and atmospheric variations (barometric pressure, rainfall) are also significant.

While there have been many studies of the presence of soil gas anomalies related to volcanic and geothermal systems, there have been few which attempt to quantify those emanations in terms of fluxes of CO_2 from the systems to the atmosphere, and no attempts at mass-balance based models of geothermal systems – i.e. how much CO_2 ends up where? Such estimates of flux have tended to concentrate on active volcanoes (e.g. Allard *et al.*, **1991).**

(A)



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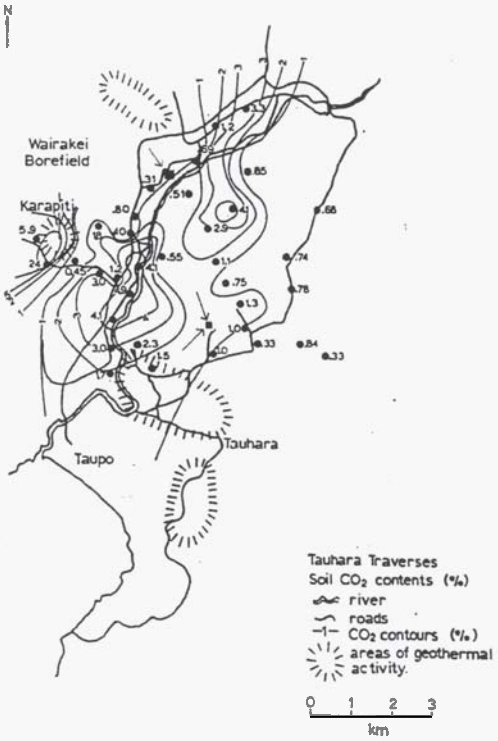

Figure 1. Location of gas flux measuring points near Reporoa **(A)** and Wairakei-Tauhara (B) - arrows indicate the positions. The contours shown are of the soil CO_2 concentrations from Sheppard *et al.*, **1988.**

In 1992 and 1993 attempts were made to measure the CO_2 fluxes at five sites at three locations in the Taupo Volcanic Zone. The sites were selected on the basis of being within contours of elevated soil-CO_2 concentrations as mapped by Sheppard *et al.* (1988), initially in areas of low soil-CO_2 concentrations and finally in a hot zone within much higher soil-CO_2 concentration contours (See Fig. 1).

2. METHODS

The details of the installations, instrumentation and data reduction are contained in the GNS report by Sheppard and Mroczek (2002). The apparatus illustrated in Figure 2, consisted of a flat chamber through which air was drawn by suction, entraining and mixing discharging soil air in the process. The CO_2 concentration was measured using an IR gas analyser, and this was calibrated against air and a standard gas. The soil gas concentration, soil temperature at 30 cm depth, and atmospheric temperature were also measured. The measurement cycle was run hourly and each measurement being repeated a number of times before switching to the next gas source.

The data was recorded on a data logger and downloaded onto floppy disk once per week. The data sets were inspected to determine the quality of the data being produced, and eventually reduced and analysed visually using the Compaq Array Viewer.

The major source of error in the flux measurement is probably due to pumping (air flow rates). This measure could be in error by as much as 20%, due to temperature changes and long-term drift.

Some gas samples were taken for carbon-isotope measurements, and climatic data from nearby stations was acquired from NIWA.

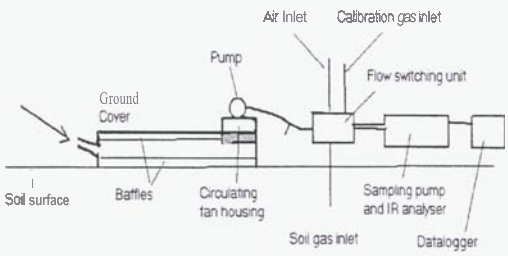

Fig. **2** Diagrammatic sketch of the gas-flux measurement system.

3. RESULTS

Plots for one set of readings from the Wairakei site and the hottest site at Reporoa are shown in Fig. 3. Perhaps the most striking aspect of the plots of flux is the obvious 24-hour periodicity of the fluxes at the Wairakei and Tauhara sites. This was the inverse of the air temperatures. In other words, the flux is highest when air temperatures are lowest. This is related to ground temperature which lags slightly behind air temperature, except at Wairakei. This site was shaded by buildings, and daily soil temperature variability was very minor, with long-term changes evident. These observations suggest that these CO_2 fluxes are biologically controlled, at their minimum when photosynthesis is at a maximum, and are not specifically temperature related. This is despite the vegetation and top few centimetres of soil (5 - 10 cm) being removed from under the chamber.

Soil gas concentrations were always greater than the concentrations under the cover. The soil gas concentrations range from just above 1% to about 7% at the Tauhara site, rarely more than 5% at the Wairakei site and were generally between 2% and 5% at Reporoa. Interestingly, soil CO, concentrations above 2% were high in relation to background concentrations found in the study by Sheppard *et al.* (1988).

Tauhara and Wairakei sites gave, in general, low fluxes of gas, and the isotopic compositions indicated that any geothermal component is more or less completely overwhelmed by biogenic modification or sources ($\delta^{13}C$ = -25°/$_{oo}$). Whether these CO_2 gases are geothermal CO_2 modified by organisms or contact with biogenic carbon has to be addressed, but it is notable that Sheppard *et al.* (1988) found variable concentrations of soil gas related to the underlying geothermal systems in terms of distributions even though the carbon had biogenic isotopic compositions.

The Reporoa CO_2 samples measured had isotopic carbon compositions which clearly indicated that the source was geothermal ($\delta^{13}C$ = -5 to -6°/$_{oo}$). Air has ^{13}C = -8°/$_{oo}$, and so is clearly distinguishable from the geothermal and biogenic component. The temperature and gas concentrations, fluxes and patterns show that the site is quite different from the other two, being hotter (up to 80°C was measured in the RH site), with higher CO, concentrations (up to 15% at site RF, 35% at RA, and over 50% at RH) and flows - up to almost 30 g/min/m^2 at the RH site, compared to a maximum of 3 g/min/m^2 at the Tauhara and Wairakei sites.

These values compare with those measured elsewhere of 0.005 to 0.4 g/min/m^2 measured by Bergfeld *et al.* (2001) in Dixie Valley, Nevada; from 0.009 g/min/m^2 up to 6.4 g/min/m^2 in the Albani Hills in Italy (Chiondini and Frondini, 2001); 0.007 to 6.9 g/min/m^2 in the Mammoth Mountain area, in California (Gerlach *et al.* 2001). It would thus

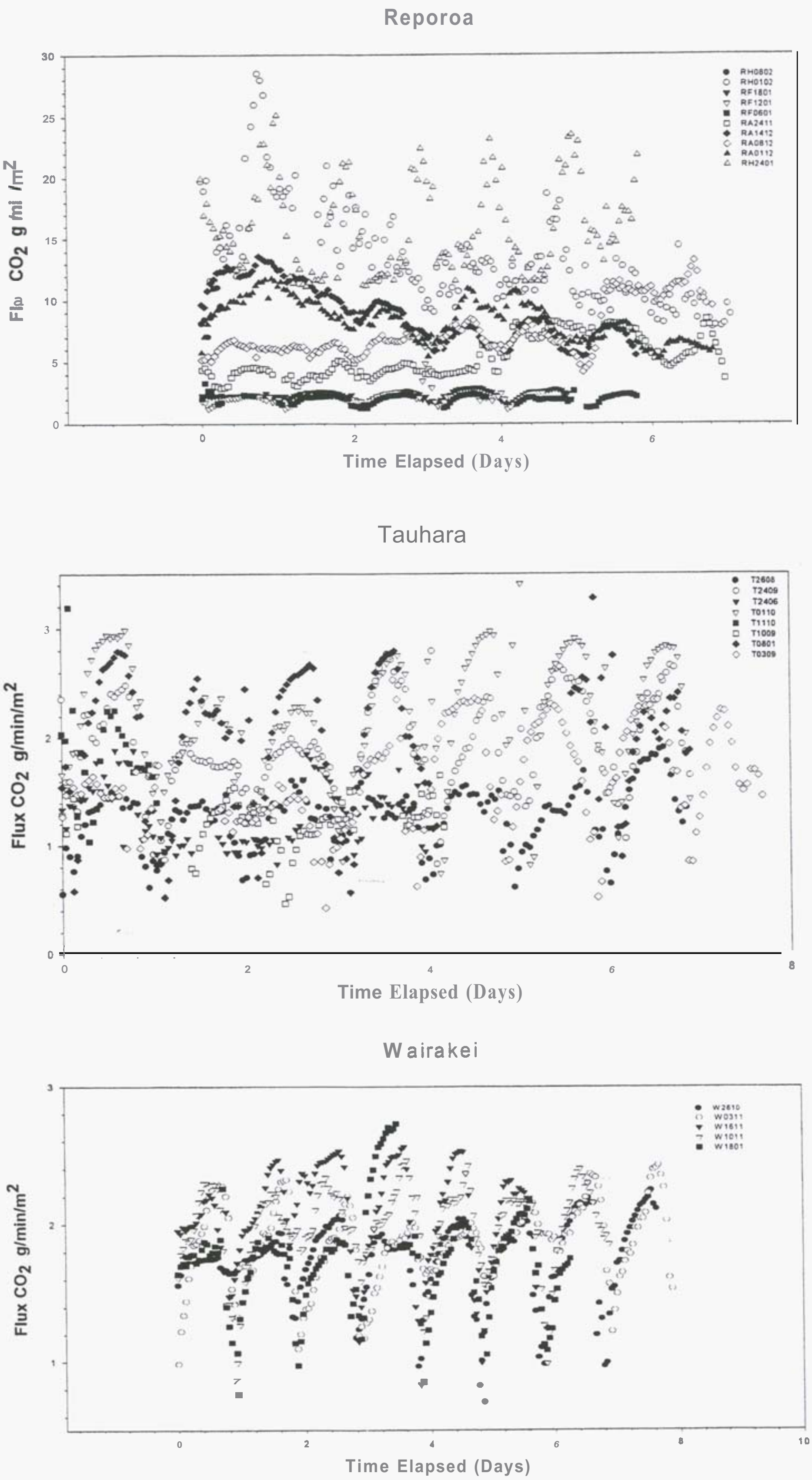

Figure 3. All CO_2 **flux** measurements from the three sites. The time refers to the time elapsed from the initiation of each run **and** has no other significance. Note that three separate sites were sampled at the Reporoa location, with the sequence RF-RA-RH passing from grassed pasture, to the edge **of** a zone of hot bare **soil** to within the hot bare **soil** adjacent to steaming ground. Note also the difference in the vertical axis scale between the top two **and** the bottom graph.

appear that the flux rates for our sites are greatly in excess of those elsewhere in the world, at baseline and maximum flows, but the Tauhara and Wairakei sites are closer to elsewhere in terms of the fluxes.

Another difference between the Reporoa sites and the other two is that the pattern of the soil CO_2 concentrations shows a maximum with air temperature at the hotter sampling site. This is taken to indicate the increasing dominance of the more direct CO_2 advection from the soil over the diffusive and biologically influenced diffusive flows.

The fluxes measured using the equipment described need to be regarded with caution, as the method has not been compared with other systems of flux measurement. The extended measurement periods give additional confidence to the measurements when compared to the single "spot" measurements usually employed, especially when the diurnal variability found is taken into account.

Heat **flows** from the Wairakei system increased significantly following the initiation of exploitation, as has the nature of the discharges, and the gas content of surface steam, at Karapiti, has increased markedly of late. The use of heat-flow as a proxy for CO, discharge would suggest that exploitation of this field has resulted in significantly increased diffuse CO_2 discharges from the field, of the same scale as the CO_2 discharged from the power station itself. This would double the carbon tax liability of the generator, if confirmed. Methane is a significant contributor to greenhouse gas discharges at Ngawha, and perhaps elsewhere.

4. CONCLUSIONS

Measurements of CO_2 flux from three sites over geothermal systems in the Taupo Volcanic Zone showed high flows in comparison with studies elsewhere in the world. The data show that in areas where elevated soil CO, contents have been mapped, but away from surface thermal features, the flux of CO, is a function of climatic conditions with air temperature, pressure, rainfall and light conditions probably playing an important part. This observation, and the evidence of the isotopic composition of the carbon in the CO_2, suggests that the flux is biologically controlled, related to photosynthetic activity of respiration of soil biota. The sampling method needs to be compared with standard methods, and the influence of climatic and other variables on the measurements needs to be quantified.

However, at sites near thermal features, the **flow** of the CO_2 is less dependant on atmospheric conditions and is most closely related to the soil temperatures. Fluxes of **up** to 30 $g/m^2/min$ were measured in bare hot ground, which exceeds any measurement recorded elsewhere in the world.

5. ACKNOWLEDGEMENTS

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