Modelling the fate of carbon dioxide in the near-surface environment at the Latera natural analogue site

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Abstract

Latera is a volcanic area north of Rome where deep, naturally-produced carbon dioxide migrates to the surface and is released to the atmosphere. The region provides an environment in which many processes relevant to the geological storage of carbon dioxide can be studied. This paper describes system-level modelling studies using Quintessa’s QPAC-CO2 code, which includes a novel soil/plant model that represents both fertilization and toxicity effects from elevated carbon dioxide concentrations. Good comparisons have been obtained between model calculations of surface venting patterns, soil gas concentrations and plant responses, giving confidence that the key features of the system are well understood.

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1. Introduction

Latera is a volcanic area situated to the north of Rome where deep, naturally-produced CO2 is released to the atmosphere from gas vents and bubbling pools. The region has been investigated by the University of Rome (and other organizations) for over twenty years and provides an environment in which many processes relevant to the geological storage of carbon dioxide can be studied, such as gas migration mechanisms and potential impact of CO2 leakage.

A conceptual model for CO2 transport at the site has been developed based on field observations, as described in Section 2. This conceptual model has been implemented in Quintessa’s QPAC-CO2 code [1], and the resulting system-level model is described in Section 3; this includes a novel soil/plant model that represents both fertilization and toxicity effects from elevated CO2 concentrations. Comparisons between field observations and model calculations over areas that include many vents are described in Section 4, and detailed comparisons at a single vent are described in Section 5.

2. The conceptual model of the site

A conceptual model for CO2 transport at the site is shown in Figure 1.

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CO\textsubscript{2} migration pathways are restricted at depth (the ‘Deep Zone’) to relatively narrow vertical zones (referred to here as ‘pipes’ or ‘chimneys’) probably associated with faults and/or intersections of faults. ‘Channelling’ will occur along the pathway of highest permeability, so that the ‘pipes’ will not necessarily be straight, but are likely to weave along the plane of the fault. Above these faults, the near-surface zone consists of heterogeneous layers of alluvium and various volcanic products. The heterogeneity of these units is assumed to cause one or multiple minor pathways associated with each major ‘pipe’.

### 3. The systems model

A model of the system has been implemented in QPAC-CO\textsubscript{2} by considering three subsystems: the deep zone, the near-surface zone and the soil/plant system. Here the modelling of the deep zone is straightforward as it effectively just supplies a flux of CO\textsubscript{2} to the near-surface zone.

Representing the relevant processes in the near-surface zone is more complex. If one considers a vent field of the type seen in the Latera region, consisting of localised high flux sources separated by very low or zero flows, one could expect two general types of behaviour in the near-surface. The form of behaviour expected between the localised high fluxes, where the vertical flux towards the surface is relatively weak, is illustrated in Figure 2. The model indicates that the CO\textsubscript{2} may ‘pool’ above the water table because its density is greater than air and may then be transported laterally. With stronger vertical fluxes associated with ‘vents’ or other small-scale features, venting occurs at the surface as illustrated in Figure 3. The size and distribution of the surface vents depends on the distribution of permeabilities of the near-surface layers.
The soil/plant subsystem model includes an innovative representation of the effects of CO₂ on plants (Figure 4). The model can be applied to pasture or arable crops and can be considered to have three components:

- plant growth;
- carbon cycling in the plant-soil system; and
- effects of changing CO₂ inputs on both plant growth and carbon cycling.

Plant growth is taken to depend on a time-integrated temperature, expressed as degree-days [2] relative to a base temperature at which growth ceases. This enables seasonal effects to be represented, but the model does not represent diurnal variations in plant respiration and photosynthesis as these short timescales are not of interest. Thus, only the net uptake of carbon to produce biomass is included in the model. The plant growth rate under optimum conditions is modified by factors dependent on the soil moisture status and CO₂ availability. Initially, for CO₂ levels in the plant canopy above present-day levels, fertilization effects are seen [3], but as CO₂ levels increase toxicity effects dominate and standing biomass levels decrease and ultimately plant death occurs [4].

The model includes the recycling of biomass which degrades to form organic material and microbial biomass in the soil. Microbes respire CO₂ and organic matter can eventually degrade to yield CO₂, and so the model represents these sources of CO₂ in the soil horizon, including their sensitivity to abiotic conditions [5].
4. Venting patterns

The chosen study area contains twenty vents, identified by a variety of methods [6], [7]. The vents are relatively well constrained in size, falling in a range from 10 to 80 m across, but typically being of the order of 35 m. The variability of the nearest neighbour distance is quite large, reinforcing the observation that the vents are clustered, reflecting the underlying fault geometries and channelling of CO$_2$ at fault intersections.

Model calculations employed a stochastically generated permeability field to represent CO$_2$ migration from depth, with an example calculation of CO$_2$ fluxes at the surface, on a 50m by 50m grid, shown in Figure 5. This shows localised high flow points (0.05 kg CO$_2$ m$^{-2}$ day$^{-1}$; red) with a generally low background flux of CO$_2$ (less than 1E-10 kg CO$_2$ m$^{-2}$ day$^{-1}$; blue) across the domain, consistent with the field observations [7]. Approximately a quarter of the CO$_2$ entering the near surface from the deep geosphere did not reach the surface, and is lost through lateral flow or dissolution in groundwater, showing that the large-scale localisation of CO$_2$ fluxes is probably caused at depth rather than the immediate near-surface.

The soil/plant subsystem model can be used either coupled to the near surface processes subsystem or independently. Figure 6 shows an example calculation, using the coupled model on a 50 m by 50 m grid, with 5 m grid size, of the effects geosphere CO$_2$ fluxes on vegetation (grass and clover). The geosphere CO$_2$ flux ranges from 0 (dark blue) to 0.28 (red) kg CO$_2$ m$^{-2}$ day$^{-1}$. In the absence of a geosphere flux of CO$_2$ the vegetation biomass is 1.6 kg C m$^{-2}$ (lime green). In the areas where venting is observed, both fertilisation (up to 2.2 kg C m$^{-2}$, red) and toxicity effects (down to 0.5 kg C m$^{-2}$, dark blue) are seen.

The calculations undertaken to date are broadly compatible with the field observations [8], but more detailed quantitative comparisons are currently being undertaken.
5. Observations and model calculations for a single vent

The field observations described by Beaubien et al. [8] have been used in making comparisons with model calculations for a single vent. During field campaigns in September 2005 and June 2006, data were collected along a 50 m transect which extended northwards from the southern side of the non-vegetated central zone of the vent, thus passing from no vegetation, to a transition zone of stressed or impacted vegetation, to background conditions. Soil gas samples were taken at 1m intervals along the profile to analyze for CO₂ concentrations at various depths, both in the root zone (10, 20 cm) and below (50, 80 cm). At the same time vegetation types and health were assessed along the entire length of the transect, visually defining the percentage cover of identified plant groups at 0.5 m intervals using a 0.5 m x 0.5 m quadrat. For the purposes of this study the vegetation observations data were expressed as ‘full’ (i.e. healthy), ‘die-back’ (i.e. stressed vegetation) or ‘bare’ (i.e. bare soil with no vegetation). In order to make comparisons with model calculations it was assumed that the ‘die-back’ vegetation had a density of 50% of the ‘full’ vegetation, giving an estimate of how vegetation biomass might change with soil CO₂ flux. Example comparisons between observations and model calculations are shown in Table 1 where the three locations at 8, 11 and 48 m along the transect are denoted by D₈, D₁₁ and D₄₈ respectively.
Table 1: Comparisons between field data from a single Latera vent and model predictions

<table>
<thead>
<tr>
<th></th>
<th>Measured</th>
<th>D_8</th>
<th>D_11</th>
<th>D_1e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil CO₂ flux (kg[CO₂] m⁻² d⁻¹)</td>
<td></td>
<td>0.25</td>
<td>0.11</td>
<td>0.002</td>
</tr>
<tr>
<td>Soil CO₂ concentration at 20 cm depth (%)</td>
<td></td>
<td>28</td>
<td>19</td>
<td>0.3</td>
</tr>
<tr>
<td>Vegetation biomass as a percentage of optimum biomass (%)</td>
<td></td>
<td>37</td>
<td>21</td>
<td>0.6</td>
</tr>
<tr>
<td>Derived from botany survey</td>
<td></td>
<td>44</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Modelled</td>
<td></td>
<td>43</td>
<td>77</td>
<td>100</td>
</tr>
</tbody>
</table>

Again, measured and modelled values are in good agreement, but more detailed quantitative comparisons are currently being undertaken for a number of measured quantities. Changes in both vegetation growth and species composition have been observed at Latera [8] and in controlled field experiments in the UK [9]; the model will be extended to examine the potential for a shift in vegetation species composition as a result of increasing CO₂ concentrations in the soil and plant canopy.

6. Conclusions

Systems modelling of the Latera site is helping to demonstrate that the key processes for the transport of CO₂ and its effects on the ecosystem are well understood. Experience at natural analogue sites such as Latera is directly relevant to the development of site-specific models for geological storage sites.

Obtaining a better understanding of the potential impacts of natural CO₂ that returns to the near-surface environment from depth provides an essential input into developing regulatory criteria for the geological storage of anthropogenic CO₂. In addition, understanding how vegetation is likely to respond to CO₂ leakages from depth could provide a valuable input to site monitoring, as observations of changes in patterns of vegetation growth could provide an early warning of possible leaks.

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8. References
