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X-ray CT imaging and image-based modelling study of gas exchange in the rice rhizosphere

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We used X-ray computer tomography and image-based modelling to investigate CO_2 uptake by rice roots growing in submerged soil, and its consequences for the chemistry and biology of the rhizosphere. From previous work, three processes are known to greatly modify the rhizophere of rice and other wetland plants: (1) oxygenation of the submerged, anoxic soil by O_2 transported through the root gas channels (aerenchyma); (2) oxidation of ferrous iron and resulting accumulation of ferric oxide; and (3) pH changes due to protons formed in iron oxidation and released from the roots to balance excess intake of cations over anions. A further process, so far not much investigated, is the possibility of CO_2 uptake by the roots. Large amounts of CO_2 accumulate in submerged soils because CO_2 formed in soil respiration escapes only slowly by diffusion through the water-saturated soil pores. There is therefore a large CO_2 gradient between the soil and the aerenchyma inside the root, and CO_2 may be taken up by the roots and vented to the atmosphere. The extent of this and its consequences for rhizosphere chemistry and biology are poorly understood.

We grew rice plants in a submerged, strongly-reduced, Philippine rice soil contained in 10-cm diameter, 20-cm deep Perspex pots. Four-week old rice seedlings, grown in nutrient culture, were transplanted into the pots at either 1 or 4 plants per pot, planted closely together. After 3 and 4 weeks, the pots were analysed with an X-ray CT scanner (Custom Nikon/Xtek Hutch; 80 mm by 56 mm field of view and 40 μm voxel size). Gas bubbles were extracted from the data by 3D median filtering and roots using a region-growth method. The images showed prominent and abundant gas bubbles in the soil bulk, but no or very few bubbles in the soil close to roots. There was a clear relation between the absence of gas bubbles and the presence of roots, as well as an increasing concentration of bubbles with depth through the soil. Analysis of the bubbles showed they were approximately 50% CO_2 by volume and 50% CH_4. The corresponding concentrations of dissolved CO_2 + HCO_3^- (NB CO_2 is 20-times more soluble than CH_4) in the soil bulk were of the order of 100 mM. We developed a mathematical model of CO_2 generation and transport in submerged soil with uptake by and transport through rice roots, and used it to analyse the images. This showed that the observed depletion of CO_2 around the roots was consistent with realistic values of parameters for the root gas permeability and rates of CO_2 production and diffusion in submerged soil.

Depletion of CO_2 around the roots will have consequences for the chemistry of the rice rhizosphere and the extent of the root-induced pH changes and other changes listed above. In continuing work we are investigating the implications for the solubility and root uptake of soil Zn, deficiency of which is a widespread constraint to rice growth.