Probing the soil-plant system ?

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Soil-plant based habitats are dynamic and constantly evolving through many components that are intrinsically interconnected. A holistic approach is required in any research programme designed to study the integrity of such managed habitats. Solutions derived in isolation will inevitably present new problems. The programmes in Theme 3 integrate and extend research by combining advanced experimental techniques with theoretical modeling. The aims are to define the essential elements of the system and to devise and deploy plant genotypes that will maintain the system's resilience and productivity.

The arable system is driven by the primary production in crops, weeds and plants of hedgerows and field boundaries. Energy, from the sun, enters the biosphere, converting atmospheric carbon dioxide and soil water into sugars. In a complex of reactions, using nutrients obtained from the soil, plants produce many other chemicals and grow. Their vegetable matter is eaten, and used by animals to make their own tissues, or returned to the soil surface as litter. Respiration, by animals, plants and microorganisms returns carbon dioxide to the atmosphere directly. Decomposition of the dead remains of all these by microorganisms returns more of this carbon to the atmosphere, while some of the converted carbon dioxide remains as a pool of fixed carbon, as a standing crop of plants and animals or as soil organic matter (Fig. 1). These standing pools are dynamic and as some fixed carbon is gained, some is also lost; the two processes may not be in balance. Much of the organic material is used to provide energy to the primary decomposers (Fig. 2), leaving a surplus of nitrogen, as ammonium-nitrogen. So the carbon cycle is linked to the nitrogen cycle by the release of ammonium-nitrogen, which is then further transformed by a range of bacterial functions. By such pathways, the 'fixed carbon' is used as a source of energy, which is transferred through the biosphere.

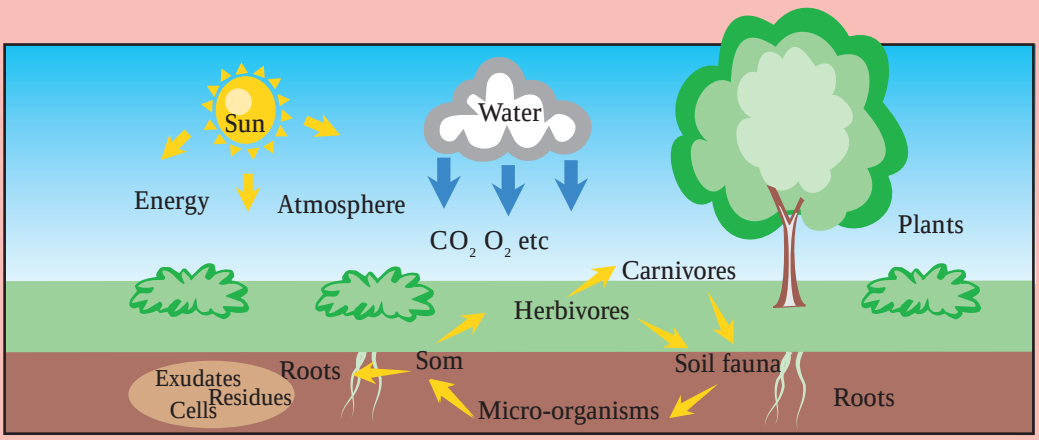

Figure 1 Carbon cycle

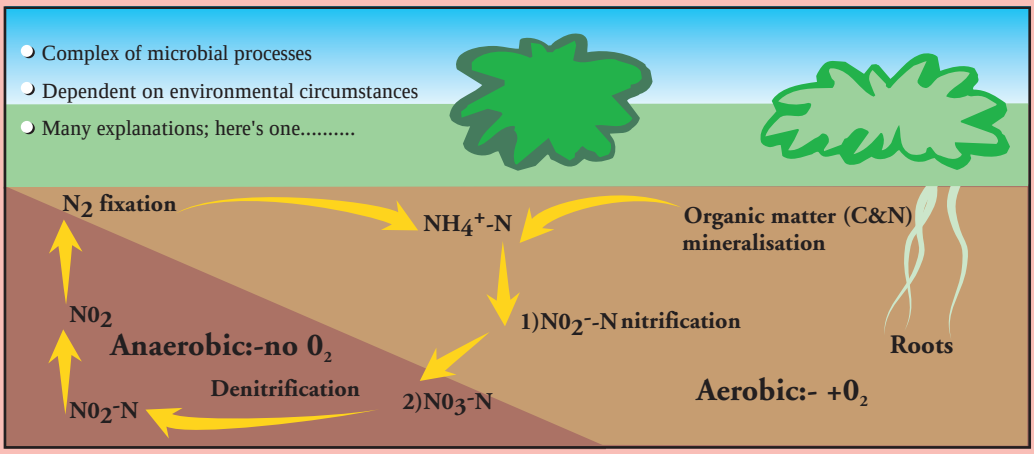

Figure 2 Nitrogen cycle

These two cycles and the links between them are basic to the functioning of the system. They have to be maintained globally and locally to ensure continued production in the habitat and to avoid wider environmental problems. Soil must be enriched and stabilized, nitrogen kept within the system and not leaked away, atmospheric carbon dioxide levels prevented from rising and harmful organic compounds degraded within and not lost to cause damage elsewhere. Since regular offtake of grain or other materials is necessary, large disturbance is unavoidable, so factors conferring resilience to change are more important than factors conferring stability. It is often assumed, for instance, that resilience requires species diversity - but how much is required? And how much and of what form is required to maintain the system in good working order, as distinct from satisfying the aesthetic requirements of humans?

The difficulty in answering such questions is that most of the action occurs at very fine scales in soil structures that are currently impossible to observe *in situ*. Accordingly, we have developed a range of innovative concepts and techniques for probing the soil-plant system so as to link the steps in Figs 1 and 2.

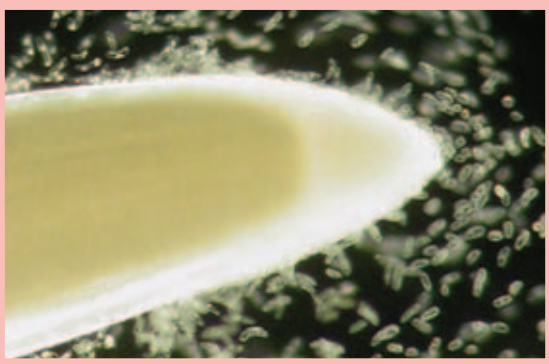

Figure 3 The primary root of maize can shed >5000 border cells in a single hydration event. We are studying the role of these cells, and their associated exudates, in physical and biological interactions in the rhizosphere, using fluorescent reporter genes, measurement of root growth pressures, and kinetic analysis of nematode motion. Border cells both decrease the mechanical resistance to root penetration, and may act as biological decoys in the rhizosphere, influencing pathogens and biocontrol organisms.

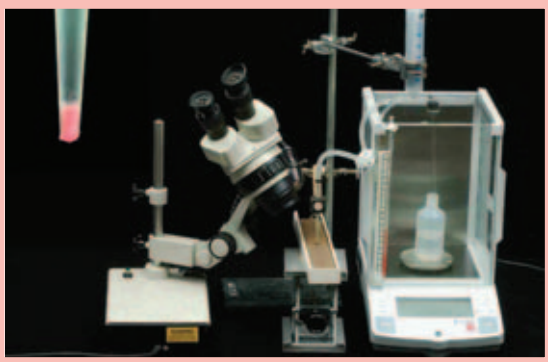

Figure 4 A novel miniature infiltrometer probe designed to measure soil hydraulic properties at the rhizosphere-scale. The rate of wetting of soil by water and alcohol solutions indicates the nature of the organic coating on the surface of soil particles. The probe (0.4 mm radius) has successfully demonstrated differences in hydrophobicity between rhizosphere and bulk soil; effects which are species (root and microbial exudate) dependent.

Figure 5 We have developed the biological thin-section technique, and used it to study the spatial distribution of micro-organisms and pore-space in soil. This has been used to develop 3-dimensional models of organism distribution in relation to water and solute (including pesticide) transport

Highlights include thin sectioning and modeling techniques for quantifying pore structure and microbial distribution, elucidating the physical and biological roles of root exudates and border cells in providing carbon sources and signaling compounds for soil microbes, and molecular profiling of microbial communities. Figures 3 -9 gives examples of the methodologies and results and their role in elucidating biophysical and biological interactions.

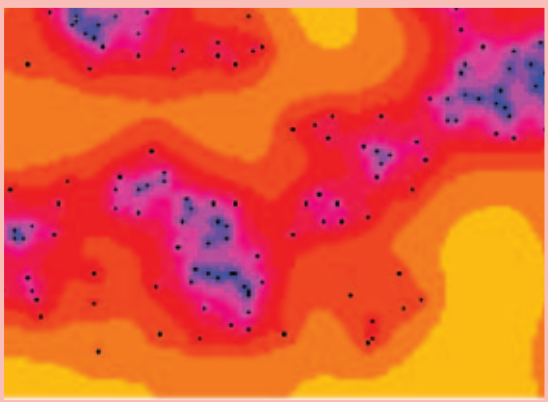

Figure 6 Mechanistic models of water and solute transport, and root uptake at scales from an individual root in a structured soil (horizontal section through 3-D lattice-Boltzmann model; LHS, above), to clustered distributions of roots from neighbouring plants (finite element model; RHS). Root function can be therefore be studied theoretically in field soils, with structures quantified using the thin section technique.

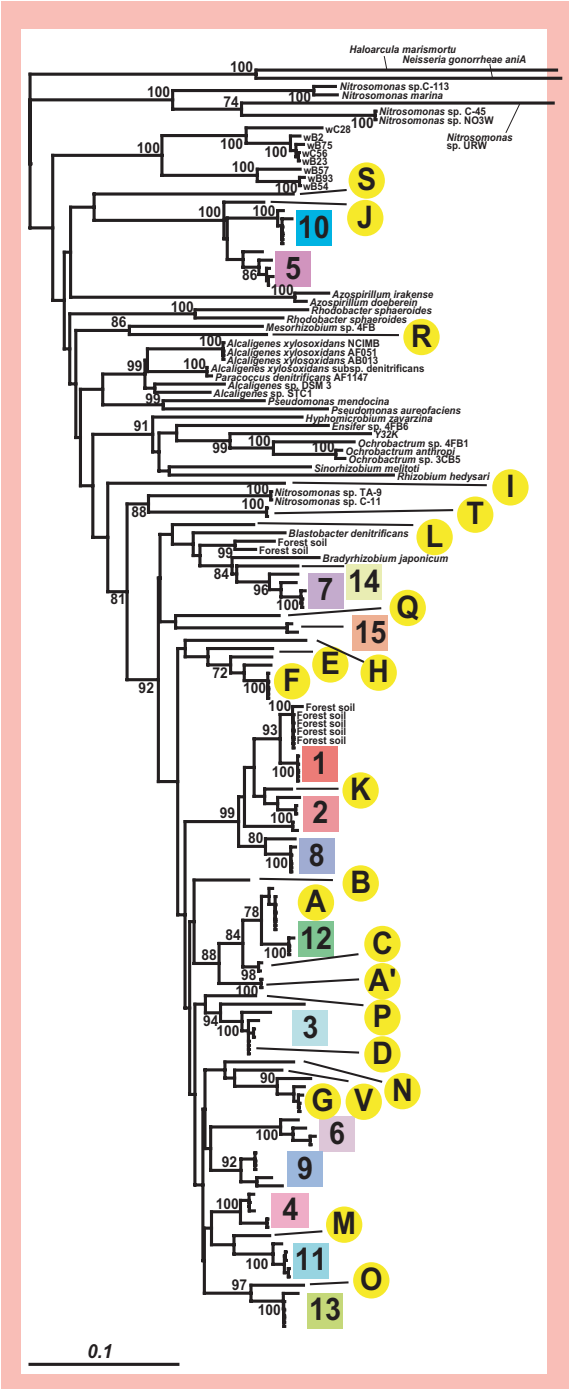

Figure 7 A phylogenetic tree showing relatedness between types of denitrifying bacteria isolated from an upland grass system. DNA was amplified from environmental samples taken from the Scottish borders. Sequences in black are markers from databases. Sequences in circles were isolated from mineral soil samples and sequences in boxes were amplified from plant roots (rhizoplane samples). The tree was produced using a neighbor-joining method and bootstrap support is shown where above 70%.

Figure 8 This bacterial feeding Caenorhabditis sp. Is characteristic of nutrient-rich conditions. The response of other soil nematodes to environmental changesis a bioindicator of soil health and function

We have, therefore, a suite of biophysical and molecular probes with which to assess the functioning of the soil-plant system. They will be combined with methods in plant and invertebrate population biology to prescribe criteria for a resilient and well functioning arable ecosystem, in which the flow of resource is well balanced between the crop and the wider food web, and losses from the system minimized. The capacity of our research to bridge disciplines of plant molecular sciences, genetics, physiology, microbiology and soil biophysics, will then be channeled into a major initiative on the genetic basis of root deposition through border cells, exudates and skeletal remains. Our aim is to guide plant geneticists and breeders as to the 'system-enhancing' traits that can be incorporated into new crop varieties.

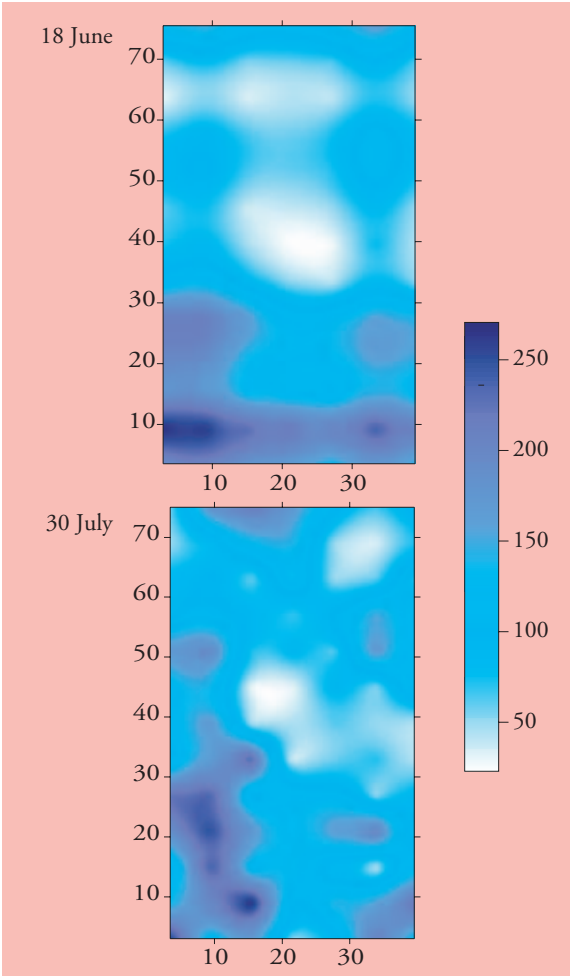

Figure 9 Kriged maps of potential nitrification rates in a barley field showing changes over a six week period in 2001. Rates of nitrate formation range from extremely high to very low, 450 to >20 mg NO3--N kg-1 hour-1, and have been shown to be extremely variable both spatially and temporally.