Plants, soils and environment

John W. Crawford

Work within the Plants, Soils and Environment theme is concerned with improved understanding of the ecological, physical and biological processes which impact on the management of agricultural and semi-natural systems. These processes operate across a vast range in scale from the molecular to the regional. They do not operate in isolation but are strongly interactive, and the greatest challenge in our research is to develop our understanding to account for the role of these interactions in the system-scale behaviour. The work is therefore integrative and multidisciplinary, and interfaces with most of the thematic programmes at the Institute. Our applied focus is underpinned by a strong fundamental and strategic science base.

Agriculture is facing its most important challenges as the millennium comes to a close. On a global scale, population is expected to increase by 64% over the next 20 years and if global nutrition is to be brought to a more equitable state, this will be accompanied by a substantial increase in the demand for food. At the same time, a reduction in the natural fertility of soil is causing an estimated 17% decrease in productivity and, although pesticide applications have increased 10-fold since 1945, crop losses have doubled as we lose the selection battle against the development of natural resistance. Against the background of these challenges, it is being realised that intensification, and the associated high inputs required by current agricultural production, is being realised at an unsustainable cost to the environment. For example, agriculture is now the main diffuse-source polluter of water. Biotechnology offers some solutions to these problems with the potential for engineering resistance and increased nutritional quality, and restoring soil fertility through remediation and structural regeneration. However, many of these technologies are in their infancy and some have their own potential problems. Durability of engineered resistance, the acceptability of genetic engineering, and concern over environmental risk are notable examples. Simply reducing inputs and putting more land into production is not the answer on its own either, since it is abundantly clear that increased extensification of agriculture has been, and would continue to be, a significant factor in the destruction of natural habitats. Therefore, as we strive for more sustainable food production, we have to recognise that no single solution is going to be the right one, and that it is likely that most progress will be made by integrating different approaches to achieve the best compromise. This requires that we understand not only a large number of different processes, but also the nature of their interactions and the consequences for the large-scale behaviour of the system.

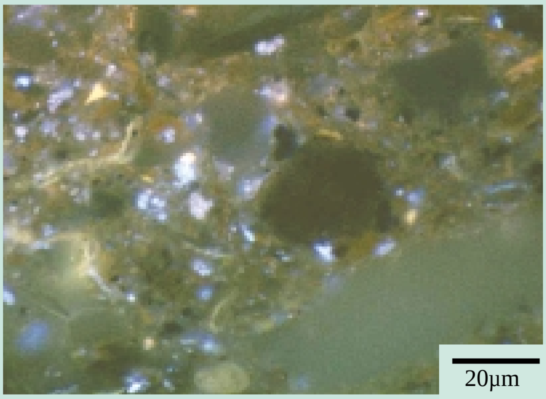

Figure 1 Thin section of soil (brown) showing bacterial colonies preserved *in situ* (fluorescent blue).

The soil system is simultaneously our most valuable and abused natural resource. Its physical architecture conducts water flow to the groundwater reservoir, while retaining sufficient quantities in the upper horizons to mediate aeration and to sustain plant, soil faunal and microbial life. Within this structurally complex habitat resides an enormously diverse microbial community. A single gram of arable soil contains more biological diversity than the entire mammalian kingdom and concurrently performs millions of complex biochemical transformations that recycle dead organic material into a form once more available for primary production. If sustainability is to be realised, this natural fertility will have to be exploited through improved management that is beyond the grasp of current understanding. We are developing theoretical and experimental approaches to account fully for the interactions between soil structure and biological functioning. As a first step, it is essential that we have techniques that allow us to directly visualise the soil physical architecture with the microbial community *in situ*. During the year, we have perfected methods for fixing the soil in hard transparent resin that are sufficiently non-intrusive that delicate biological material such as bacterial cells and fungi is perfectly preserved. This resin-impregnated soil can be cut into thin wafers and polished to a few thousandths of a millimetre in thickness, to provide us with thin sections that can be viewed down a microscope (Fig. 1). By employing a fluorescent stain of the microbes, the optical contrast between the physical architecture and the soil can be enhanced. Using digital image capture, we can process the images and analyse the spatial structures that exist both in the architecture of the soil and the distribution of the microbes. Thus, for the first time, detailed statistics relating to the relative arrangement of soil and microbes can be obtained. This precise quantification is required in order that the information can be used in mathematical theories that are being developed in tandem with our experiments on the functioning of the soil system. Such an approach is being followed in a project funded during 1998 under the Government's DTI Biological Treatment of Soil and Water LINK scheme. In the largest award made under the scheme, the DTI has commissioned the Soil Plant Dynamics Unit to work with one of the world's

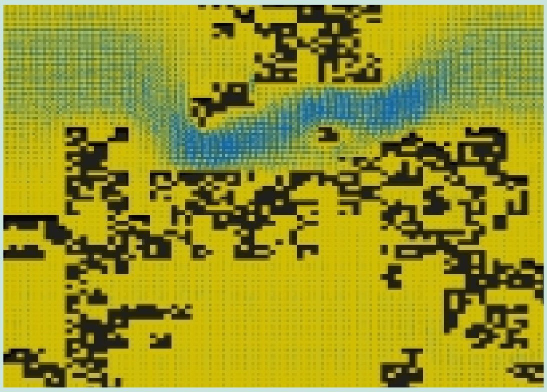

Figure 2 Computational fluid dynamics models are used to understand the impact of structure on flow paths and solute residence times.

largest agrochemical companies, Rhone Poulenc, and an environmental consultancy company, Quantisci Ltd., to study the fate of organic chemicals in soil. This project acknowledges the fact that the major uncertainties in predicting the fate of reactive compounds in soil reside in the link between pore-scale structure and the microbial activity that degrades the compounds. Using our recently developed imaging techniques, we will link the quantitative description of the soil system to models of transport with the aim of relating lab-based measurement to field-scale risk management. In a related 5-year project, SOAEFD have funded the Unit to lead an interdisciplinary research team combining groups from MLURI and Aberdeen University to study the fate of environmentally-important chemicals in two contrasting catchments: an upland nutrient-poor system, and a lowland arable system. Pore-scale models of surface reaction chemistry have been developed that demonstrate the significance of physical structure for adsorption-desorption processes, and are already providing clues to how the enormous complexity may be understood in terms of simple scaling relations between space and time. Computational fluid dynamic models of pore-scale solute flow are also being derived to understand how the structure of soil mediates the delivery of chemicals to the soil surface (Fig. 2). Our new approaches are providing insights into how the structure of porous media is related to the properties of reactive flows, with ramifications that go far beyond the current application. These pore-scale models are being linked to catchment scale models of solute flow to understand the role of heterogeneity in chemical transport at different scales (Fig. 3). In combination with the theoretical developments, a parallel programme of extensive field and laboratory studies of scaling effects on hydraulic and chemical properties is being carried out. A catchment-scale arrangement of sample points has been designed and implemented to monitor the spatio-temporal scaling properties of the physical and chemical characteristics of the catchments. This is being related to underlying, topographical, geological and soil property information that is simultaneously being gathered and is beginning to reveal simple patterns that underlie the complex behaviour of the catchments. Perhaps the most challenging aspect of our work on reactive transport in porous media is to account for the impact of unsaturated conditions – the most common state of soil where not all the pore space is filled with water. In a project funded by SOAEFD, we have been developing experiments and theory to understand the consequences of soil structure for the ability of the soil to retain moisture against suction, such as is applied by plant roots, and to understand the effect of unsaturated conditions on the connectivity of the water films. The latter property is crucial for understanding transport of oxygen, solutes, nutrients and/or microbes in unsaturated soil. By comparing our theoretical models with the results of retention measurements and quantification of structure from thin sections, we found our predictions to be accurate to greater than 5%. This confirmation of our hypotheses has revealed a fascinating scaling relation between the connectivity of water films and the applied suction. This relation leads to an important simplification in the theory and implicates a single parameter as the governing factor in determining the rate at which

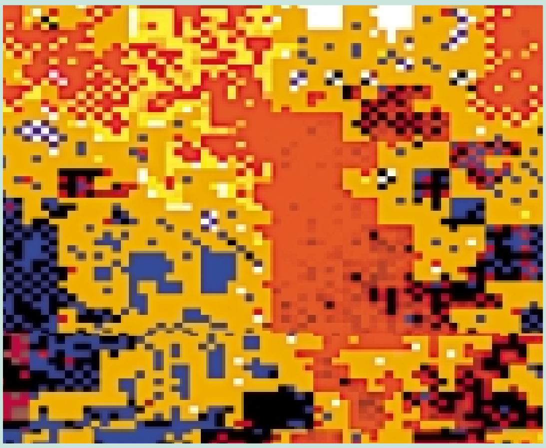

Figure 3 Simulation of chemically-reactive solute flow in a fractal soil structure (brown). Red to blue denotes high to low concentration respectively.

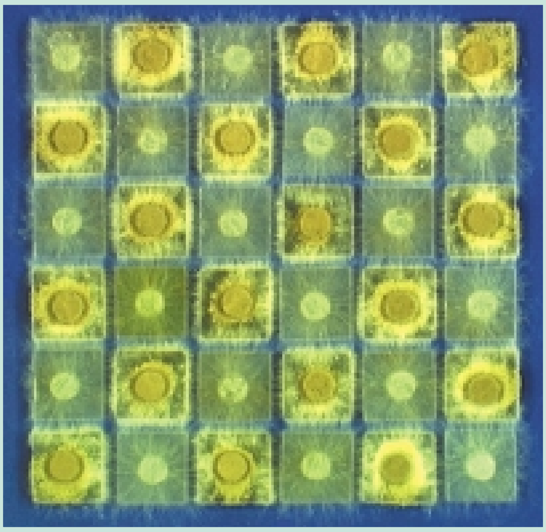

Figure 4 Tessellated agar tile system to study emergent behaviour in fungal communities.

air enters structured porous media under pressure. A fuller account of the approaches to the study of the fate of environmental compounds is provided in the Report of the Soil Plant Dynamics Unit elsewhere in this volume.

Much of our soil-related research concerns the functioning of the soil microbial community, and in both our research on microbial and plant systems, the relation between community structure and spatio-temporal dynamics is of central concern. This link is being studied in the context of soil fungi because of their important role in natural fertility, soil structure generation, soil-borne diseases and their potential for bioremediation (Fig. 4). Being non-determinate, they also belong to a wide class of organisms whose community dynamics has not been studied in detail before. In collaboration with the University of Abertay Dundee, we have been examining the dynamics of a fungal microcosm using a combination of experimental and theoretical techniques to focus on the relative importance of small and large-scale context for the behaviour of the community. We found the hypothesis that the large-scale dynamics is a consequence of independent interactions between species in a local neighbourhood can be excluded at the 5% significance level. Instead, the system exhibits emergent behaviour whereby the outcome of interactions at the individual species level depends on community-scale features. Thus, it is unlikely that experiments performed out of the community context will provide useful information on the dynamics. New types of analyses and experiments are being developed to study these systems at the community level.

One of the most frustrating facts in relation to the microbial community in soil is that it is almost impossible to measure its diversity directly. As far as is known, only about 1% of the microbial community in soil can be extracted, grown in culture and measured, while the other 99% do not grow outside the soil system. The SOAEFD-funded MICRONET project entered its second phase in 1998 and concerns the connection between microbial community structure and function, and its relation to vegetation cover and land management in low-input upland systems. We have pioneered techniques for broad-scale analysis of community structure and these have been applied to understand how the genetic structure of communities differ at separate locations. One of the key hypotheses was that there might be a strong relation between the plant species and the microbial community that develops in the soil around them, at least in systems under the same management regime. This might arise from known effects that plants have on the nutritional and physical soil environment, and because the nature of that influence is plant species and land-management dependent. Surprisingly, however, we have discovered that adjacent communities under single-species swards are as genetically distinct as those separated by hundreds of kilometres. We could also find no significant effect of plant species. Therefore, either the soil environment is extremely variable despite the above- ground cover and hides any existing signal, or there simply is no relation between above and below-ground diversity. These questions are being pursued in Phase 2 of MICRONET using new molecular tools that provide a more detailed description of the part of the community most likely to be influenced by above-ground plant cover. Techniques are following on but narrowing in scope to focus on particular functional groups and we are developing novel molecular probes for nitrite reductase activity to characterise the denitrifying fraction of the community involved in denitrification. We have also secured two further grants under the NERC soil biodiversity initiative that aim to explore further the relation between the diversity of the microbial community and the soil environment. These projects will be carried out in collaboration with the Universities of Aberdeen and Stirling.

An additional link between above and below-ground processes is provided by our research on the dynamics of weed seedbanks. This work, carried out with substantial funding from MAFF and in collaboration with ADAS, examines the effect of various levels of management intensity on the changes in diversity of weed seeds in the soil. Management options included crop rotation and herbicide, and, although there was some interaction between these, it was the latter that had the most significant impact on the seedbank. In general, seedbanks declined in total number as herbicide applications were increased. However, an interesting relation between species number and total seedbank was discovered, demonstrating the fact that increased weed species diversity is accompanied by an exponential increase in seedbank levels. Thus, under high herbicide inputs, very few weed species remained in the seedbank, but they coexisted in similar low abundance. Under low inputs, there were more species and some of these existed in very high abundance.

Our studies on vegetation systems continue the theme of exploring the role of individual behaviour in the dynamics of communities. The 5-year SOAEFD-funded Vegetation Dynamics programme is coordinated within the Plants, Soils and Environment Theme at SCRI and is a collaboration between SCRI, SAC and the MLURI. The overall goal is to understand the species composition in an upland grazed system, and we have responsibility for the theoretical aspects. A surprising finding of the work so far is the remarkable diversity that exists in what was previously thought to be a largely clonally-propagated system. The community is therefore rather well described as comprising distinct individuals. Parallel theoretical approaches are being used to synthesise this otherwise overwhelming complexity and to understand how such diversity can coexist. Results of the analyses so far indicate that communities of randomly assembled individuals cannot coexist in general and that the dynamical state and the stability of that state arise from interdependencies between the functional traits of individuals.

An important aspect of our studies on plant systems is the possible impact of genetically-modified organisms (GMOs) on the natural and semi-natural environment. Work is currently underway on a MAFF-funded project to study the regional-scale movement of oilseed rape pollen and to understand the role of regional-scale context on the rate of geneflow in the environment. Fields of oilseed rape were mapped across Tayside and bait plants and pollen traps were established to measure the spatial distribution of pollen and its viability. A theoretical model of pollen transport was also developed to aid in the interpretation of the results. We found that the measured distribution of pollen and therefore the potential rate of geneflow from agricultural fields into the environment is determined by the regional scale distribution of fields. The apparent rate of decline in pollen concentration from the nearest oilseed rape field is also determined by the regional context. This confirms our earlier conclusions that estimates of geneflow obtained from small isolated plot experiments tend to underestimate the characteristic distance over which geneflow can occur in a more realistic context.