Environment Plant Interactions

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Research in the EPI Programme seeks to describe, understand and predict how the environment impacts on plants, and how plants modify their environment – an environment that changes physically, chemically and biologically in both space and time. We focus on the efficient use of resources, such as light, carbon, water and minerals, and the development of sustainable and resilient arable ecosystems fit for global and environmental change.

The soil provides the substance in which plants grow and the mineral elements for their growth; it retains the water necessary for life, and contains the carbon to sustain the activities of micro organisms. "The nation that destroys its soil destroys itself," said Franklin Roosevelt in 1937 when he urged state governors to adopt soil conservation laws at the end of the dust bowl. Seventy years on, soil degradation and its impact on global food production has prompted unprecedented media coverage of this most precious natural resource. In 2008, an issue of *National Geographic* was dedicated to soil, with articles describing the threats of erosion, drought and reduced fertility, the Royal Agricultural Society of England (RASE) published a report identifying the threat of soil degradation to food production, and the Scottish Government had consultations to develop a 'Scottish Soil Framework' aiming to preserve the capacity of soil to produce crops and provide environmental services. Members of EPI are contributing significantly to improving the management of soil, through their work on ecological resilience and the alleviation of environmental constraints to crop production.

Future agroecosystems that deliver crop production with minimal environmental impacts require that the soil and biota, mineral inputs and losses to air and water all remain within specific bounds. Losses to the wider environment, in particular, need to be drastically reduced. In collaboration with colleagues at Warwick HRI, we have recently estimated phosphorus (P) loads to GB waters from agricultural sources to be 20% of the

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total P load, representing less than 3% of the P input to agriculture but still an important contribution to nutrient enrichment and eutrophication in surface waters. Similarly, in collaboration with the University of Aberdeen and SAC we have determined that nitrogen (N) fertilisers contribute most of the greenhouse gas (GHG) emissions from arable agriculture. Members of EPI are therefore developing strategies to reduce P and N inputs to agriculture by improving fertiliser management techniques and by identifying genotypes with improved fertiliser acquisition and physiological use efficiency.

Liberty and limits to optimise agroecosystems To maintain agricultural production whilst improving ecosystem services, anthropogenic inputs, abiotic constraints and trophic interactions must be maintained within

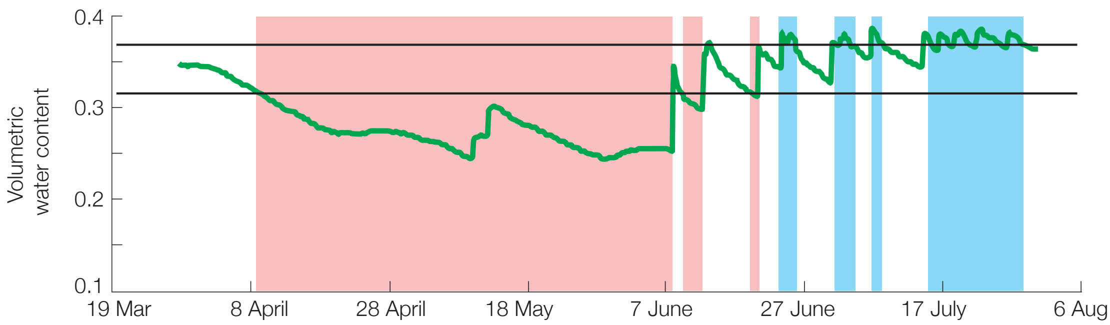

Figure 1 Variation in the volumetric water content of soil over time at SCRI showing periods when roots were likely to be limited by mechanical impedance (pink) and shortage of oxygen (blue).

appropriate ranges. Work in EPI has helped to identify these ranges, recently addressing various properties of soils, such as carbon content and compaction. For example, a least limiting water range can be defined for a soil, below which mechanical impedance or drought, and above which lack of oxygen, limit root growth. Even in the comparatively good soils of the SCRI farm, mechanical impedance restricted root growth in the dry period from April to May in 2008, and the subsequent, unforgettable rainfall raised water contents to risk levels for oxygen diffusion on four occasions, including one occasion lasting almost two weeks at the end of July (Fig. 1). A second example is that food webs must contain, or have available, a minimal carbon content for their upkeep. To enable soil micro organisms to carry out nutrient cycling and soil to remain stable, the carbon content in mineral soils should ideally be no lower than 2% of soil mass; a figure that is usually several times greater than the annual carbon intake by photosynthesis. Probably around 1–2% of the annual carbon budget is required in the form of wild arable plants to fuel the food webs of the soil surface and vegetation in the ploughed areas of field. As the total carbon is used, it needs to be replenished by additions in the form of roots and dead biomass. If the harvest takes too much material, or soils are repeatedly tilled, then the carbon content drops below the optimal range. Similarly, if the wild plants are removed, the arable food web will collapse.

There was great uncertainty, however, as to whether arable soils in Scotland were within 'safe' ranges for variables such as these. Essential baseline information was therefore gained through a major study on a total of 109 fields across 55 farms in the east of Scotland during 2007 and 2008. With SAC, arable fields were surveyed for soil properties, biodiversity, yield and agronomy, covering a wide range of management intensity and geographical location from Moray to the Borders. The results identified some worrying trends for arable east Scotland. Topsoils with carbon contents at or below a critical threshold of 2% were found on more than half the farms surveyed. A tenth of the topsoils sampled were highly compacted and susceptible to oxygen starvation when wet. Measurements of penetration resistance suggested root elongation would be mechanically restricted in a third of all topsoils sampled. The low average soil carbon content and large physical resistance to root growth will have decreased primary production and crop yield below the climatic maximum. More nutrients need to be applied to such problem soils to achieve a given yield, while losses of nutrients to the air as greenhouse gas equivalents and to water through surface run off are both increased. Research in EPI is tackling these major problems through defining methods to improve the condition of soils and food webs and to raise the efficiency in the use of nutrients.

Sustainable mineral nutrition of crops In addition to oxygen, water and carbon dioxide, plants require 14 mineral elements. A lack of any of these impairs plant growth and crop yield. Mineral elements cannot be synthesised by a plant but must be acquired from the soil solution by its root system. Six mineral elements, N, P, potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S), are required in large amounts. These are termed ‘macronutrients’ and supplied as inorganic fertilisers, mineral rocks or organic manures to maximise crop production. Other mineral elements must also be supplied to crops if they are lacking in the soil. Concentrations of mineral elements in plant tissues generally exceed those in the soil solution (Fig. 2) and this requires plants to invest energy into their acquisition.

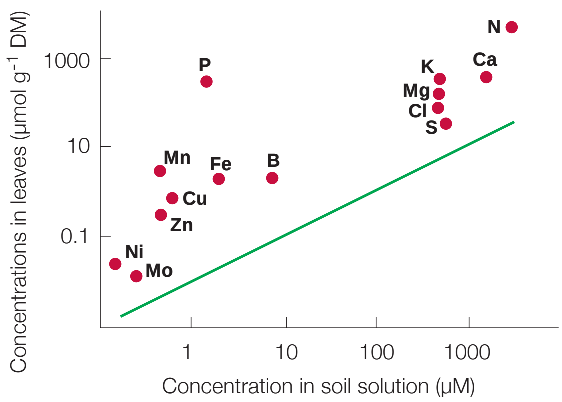

Figure 2 Concentrations of the 14 essential mineral elements in the soil solution and in leaves of plants. The line indicates equimolar concentrations in soil solution and plant leaves.

Phenotyping barley varieties.

The management of plant mineral nutrition is central to sustainable agriculture. Essential to the agricultural revolution was the synthesis of N-fertilisers from nitrogen in the air using the energy-driven Haber–Bosch process and the patented production of P-fertilisers from rock phosphates using sulphuric acid. However, the synthesis of N-fertiliser contributes significantly to the production of GHGs, losses of N and P from agricultural land contribute to the processes of eutrophication, and it has been estimated that commercially viable sources of P and S will be exhausted within 50 years. For all these reasons, alternative sources, and effective recycling, of mineral elements for agricultural production must be found.

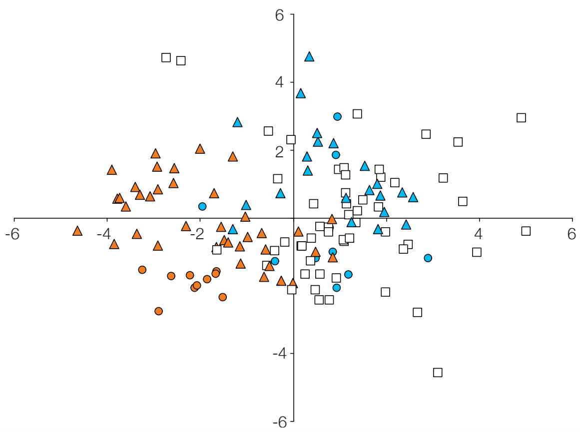

Figure 3 Phenotyping barley varieties for plant development and nutrient use and statistical plot (principal components analysis, PCA) derived from phenotypic data showing separation between two sets of mutant lines (blue and orange) and commercial varieties (white).

In EPI, we are pursuing two complementary approaches towards sustainable mineral nutrition of crops. The first is agronomic, where we aim to minimise the application of conventional inorganic fertilisers through soil management, fertiliser-placement, scheduling and decision support techniques. Employing these techniques in an integrated farming system could halve the fertiliser burden. We consider the agronomic approach to lead to the greatest improvements in the shortest time. The second approach is through genetics and is founded on the observation that crops that yield best with reduced fertiliser inputs are those whose roots acquire mineral elements from the soil most effectively and produce higher yields from a given plant nutrient content.

Historically, the application of agronomy and genetics to intensive agriculture has attempted to maximise specific aspects of crop physiology, such as the rapid expansion of leaves or the partitioning of biomass from foliage to seed. In many environments, however, plants are subject to multiple constraints and phenotypic specialisation tends to render them more susceptible to acute stress at some point during their life cycle. We are therefore working through concepts, experiments and models to enable the design of plants and crop systems in which the underlying components of survival, growth and fecundity are balanced and the resulting plants and crops are more resilient to environmental change.

Harnessing genetic variation We are studying genotypic variation, environmental plasticity, and the genetic basis of important traits and processes including root system architecture, the root–shoot balance, the uptake and use of mineral elements, biochemical processes that increase the availability of mineral elements in the soil and tolerance to abiotic stress (Fig. 3). New methodologies are being developed. For instance, a four-year collaboration with the universities of Cambridge and Dundee has produced PlantVis, in which confocal microscopy is combined with image analysis to identify growth parameters in specific root zones at cellular resolution (Fig. 4). Using these and other methods, we have identified large between-species and within-species genetic variation in many relevant traits. Ample genetic variation has been found in barley for traits which affect growth in compacted soil and the acquisition of water and minerals. In the field, a screening approach has been developed to identify barley genotypes that have a greater capacity to discover biopores that serve as conduits across mechanically impeded plough-pans, providing rapid growth pathways to otherwise inaccessible resources. Over 50 barley lines have been tested in EPI's long term tillage experiment which compares direct drilling, minimum tillage, ploughing or deep ploughing. Several promising genotypes have been identified that could be developed for farming systems employing reduced tillage.

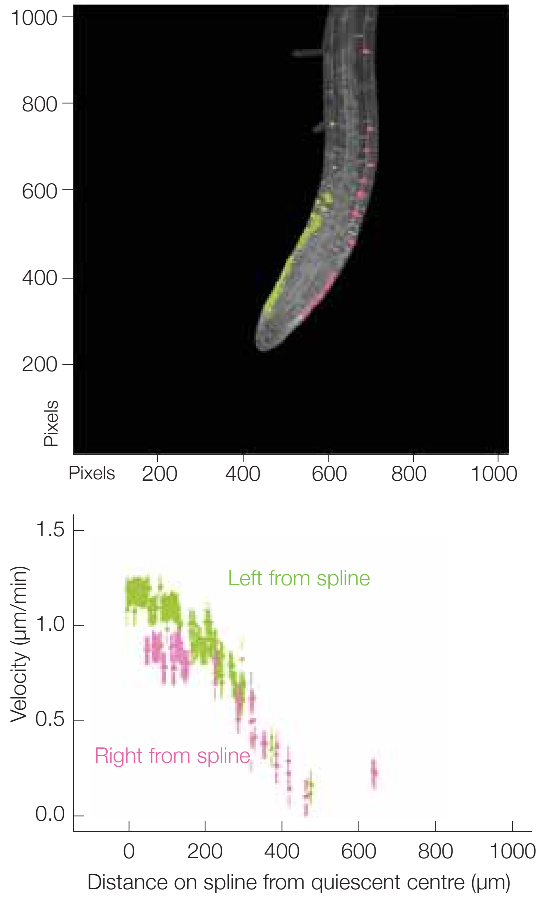

Figure 4 Sensitive image analysis tool (PlantVis) developed in collaboration with the University of Dundee for estimating motion in living organs: examples show (upper) image of growing root with two areas selected for estimating growth rates, and (lower) the velocity of these expanding regions relative to the distance from the quiescent centre. Spline = line drawn through the central longitudinal axis of root.

Chromosomal loci and genes have been identified that increase the acquisition of mineral macronutrients from both conventional and alternative fertilisers

Figure 5 Aerial photograph of a field experimental site where the effects of compost and slurry amendments to soil are being investigated.

and that improve the physiological use efficiency of mineral macronutrients in brassica, cereal and potato crops. While such information is valuable to breeding programmes, genetic contributions to resource acquisition are often complex and environmentally-dependent, since plants employ combinations of diverse strategies to optimise their acquisition of water and mineral elements. Plant husbandry and fertiliser management must also be considered therefore, when producing crops that use water and fertilisers most effectively.

Field management for offtake, food quality and sustainability Carefully targeted additions or interventions can often lead to rapid beneficial change. Here are two examples of the way EPI is taking research to practice. In the first, methods are being developed to supplement, or replace, inorganic fertilisers with alternative fertilisers, such as composts from urban green wastes, animal manures and struvite (an abundant ammonium magnesium phosphate reclaimed from sewage). We are also investigating the use of legumes and microbial inoculants to improve the availability of essential mineral elements. A major development this year has been to test quality composts made from urban green wastes (the cuttings, clippings and weeds from gardens and public spaces). These soil amendments can restore some of the carbon and nitrogen lost from soils and improve their structure, water retention and workability. Supported by the Waste and Resources Action Programme (WRAP), we have established long term field trials studying the effects of these amendments on yield and quality of barley and potatoes in both conventional and organic systems (Fig. 5). Increased yields and improved product quality were found when these amendments were used as supplementary fertilisers.

The second example contributes more directly to the topic of human health. Humans require more than 22 mineral elements for their wellbeing, one of which is selenium (Se). Dietary Se intakes in the UK have declined to almost half the 1970s level, in part, a consequence of replacing North American milling wheat, which is grown on high Se soils and has a high Se concentration, with wheat grown in low Se soils of the UK. A collaboration with members of the Defra LINK BAGELS Consortium (University of Nottingham, University of East Anglia, Rothamsted Research, Institute of Food Research, Nickerson-Advanta, Velcourt, Carrs Fertiliser, Yara UK and Marks & Spencer) demonstrated that the application of Se-fertilisers to wheat crops grown in the UK increases their grain Se concentrations without affecting other quality attributes important for breadmaking. Loaves baked from this Se biofortified UK wheat, in which one slice delivered approximately 10% of the recommended daily intake, were produced by Marks & Spencer and distributed to visitors to the Cereals2008 event in Cambridgeshire.

Designing plant–soil systems for better capture and use of resources EPI is developing a strong capability in ecosystem design, combining knowledge at different

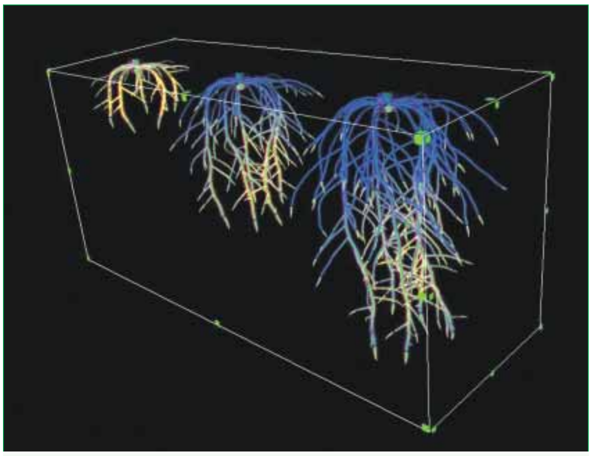

Figure 6 Computer generated figure of the three dimensional growth of a root system over time, showing the evolving regions of active nutrient uptake (yellow) and the structural framework (blue).

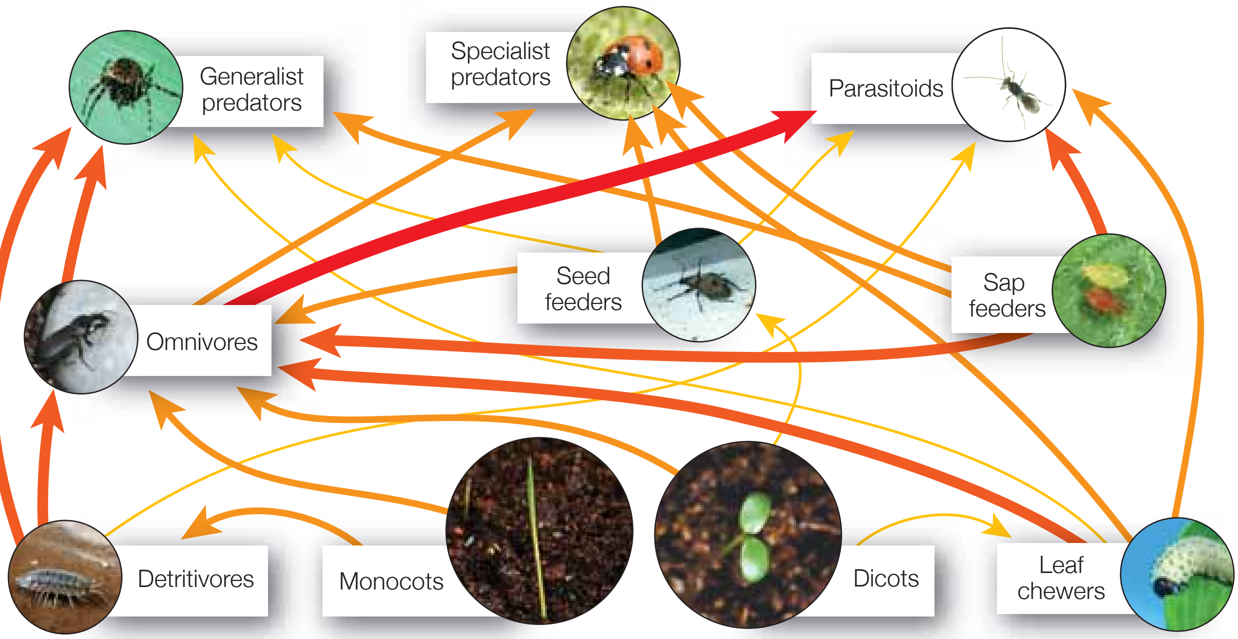

Figure 7 Schematic illustration of the main functional components of the within field arable food web based on monocot (grasses) and dicot (broadleaf) arable plants. The thickness of a line indicates the strength of the relationships between each functional group.

biological scales from the plant to the landscape to devise systems better able to meet the challenges of the future. Designs are being tested experimentally in controlled environment rooms, glasshouses and field plots. Testing will soon move to SCRI's new long term, field scale experimental platform at Balruddery Farm. Here, we give two examples of our work on system design – one for plant roots and one for the essential biodiversity in an arable production system.

Models of growing root systems are constructed to optimise the uptake of nutrients by plants and thereby reduce the input of fertiliser. The models incorporate genetically controlled mechanisms by which the plant senses and responds to environmental signals (Fig. 6). The models integrate the couplings between the biophysics of root–soil interactions, the physiology of the whole plant and the genetic control of growth and development. These structure–function models will ultimately be used to guide both the selection and breeding of crop varieties, the choice of a crop suited to local constraints and the adaptation of agronomic practice to reduce inputs.

At a larger scale, cropping systems are being designed that adopt new, more profitable crops but avoid any undesirable effects on the essential biodiversity that maintains the soil and field. A food web for the arable system has been constructed from field data (Fig. 7). A mathematical model of this food web, developed with Rothamsted Research and Syngenta through the Sustainable Arable LINK programme, is being used to assess the effect of a change in crop genotype or management on the partition of energy and matter among crops, wild plants and invertebrates. A change that reduces the important organisms below defined limits will be discouraged. Finally, the environmental and associated economic factors consequent on various options and scenarios are being examined with stakeholders using multi-attribute decision models (MADMs) developed with the Josef Stefan Institute, Slovenia.

Through its innovative, holistic research and system design, EPI is ideally placed to inform government and the public on the major challenges of the coming decades. Its expertise and contributions are central to predicting and adapting to global change, enhancing and preserving essential biodiversity in and around farmed landscapes and producing nutritious food in a sustainable way.