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## ABSTRACTS OF COMMUNICATIONS

# Proceedings of the Thirty-seventh Meeting of the Agricultural Research Modellers' Group

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EDITED BY

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This group, which is concerned with the applications of mathematics to agricultural science, was formed in 1970 and has since met at approximately yearly intervals in London for one-day meetings. The thirty-seventh meeting of the group, chaired by J. Craigon of The University of Nottingham, was held in the Kohn Centre at the Royal Society, 6 Carlton House Terrace, London on Friday, 8 April 2005 when the following papers were read.

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**Examining the impacts of crop cultivation on climate with a general circulation model (GCM).** T. M. OSBORNE<sup>1</sup>, J. M. SLINGO<sup>1</sup>, T. R. WHEELER<sup>2</sup>, A. J. CHALLINOR<sup>1,2</sup> AND D. M. LAWRENCE<sup>1</sup>.  
<sup>1</sup>*Department of Meteorology and* <sup>2</sup>*Department of Agriculture, The University of Reading, Reading, Berkshire RG6 6BB, UK*

GCMs are used extensively in climate science to investigate and understand past, current and future climate. In recent decades the role of the land surface in the determination of local weather and climate has been increasingly recognized. As a consequence, GCMs now include sophisticated parameterizations of the Earth's land surface and its interaction with the overlying atmosphere. In general, vegetation cools surface climate, especially in the dry season when soil evaporation is low (Osborne *et al.* 2004). The representation of the numerous plant species within a GCM grid box is restricted to a few representative plant functional types. Despite crops occupying approximately 10% of the land surface, their representation in GCMs is almost non-existent. Instead, significant cultivated areas are represented by grassland. It is important to improve upon the representation of crop growth and development in GCMs if we are to improve simulations of weather and climate of cultivated areas.

Crop growth and development routines of the General Large Area Model for annual crops (GLAM, Challinor *et al.* 2004) have been incorporated into the

land surface scheme of the UK Met Office GCM. Combining the two representations of vegetation was non-trivial due to the different model complexities. To examine tropical rain-fed groundnut production within the GCM, a potential growing region was determined based on GCM climate data. The coupled crop-climate model then simulated 17 years of crop growth and climate. The simulated crop growing seasons exhibited large inter-annual variations in both growing season frequency and crop size, implying that an interactive rather than prescribed representation of crops is required for the complete examination of crop-climate interactions. When compared to a GCM simulation with the standard vegetation distribution, the cultivation of crops tended to increase surface temperatures both before sowing and after harvest.

Tom Osborne would like to acknowledge the support of NERC during his Ph.D. and is currently funded by the EU Framework 6 ENSEMBLES project.

OSBORNE, T. M., LAWRENCE, D. M., SLINGO, J. M., CHALLINOR, A. J. & WHEELER, T. R. (2004). Influence of vegetation on the local climate and hydrology of the Tropics: sensitivity to soil parameters. *Climate Dynamics* **23**, 45–61.

CHALLINOR, A. J., WHEELER, T. R., CRAUFURD, P. Q., SLINGO, J. M. & GRIMES, D. I. F. (2004). Development and optimisation of a large-area process-based model for annual crops. *Agricultural and Forest Meteorology* **124**, 99–120.

**A mathematical model for nutrient uptake by root branching structures.** T. ROOSE. *Mathematical Institute, University of Oxford, 24–29 St. Giles', Oxford OX1 3LB, UK*

In this talk I will present a hierarchy of models that enable the evaluation of the levels of nutrient and water uptake by branched root systems from partially saturated soil. In particular, the models take into account the simultaneous uptake of highly buffered nutrients and water from the soil. First I will present a model for nutrient uptake by a single cylindrical root that will be non-dimensionalized and solved analytically (Roose *et al.* 2001). The second stage model treats water uptake and transport by the different subbranches in the root system (Roose & Fowler, 2004a). The main finding of the analysis is that some subbranches are less effective at taking up water and transporting to the shoots than main tap roots due to their anatomical structure. Finally, the root water uptake models will be combined with nutrient uptake models in order to evaluate nutrient concentration gradients in the soil (Roose & Fowler, 2004b). Using this final model I will show that previous models by Barber, Tinker and Nye can systematically underestimate the phosphate uptake, due to their over-simplified approach in dealing with root branching structure. I will show how this discrepancy can be remedied without the need for extensive three-dimensional computer simulations. In particular, I will discuss how the rigorous application of the method of spatial averaging can give better estimates for phosphate uptake by field crops. Whilst the spatial averaging presented in Roose & Fowler (2004b) does introduce approximations, it does so without neglecting any necessary root structural effects.

- ROOSE, T., FOWLER, A. C. & DARRAH, P. R. (2001). Mathematical model of plant nutrient uptake. *Journal of Mathematical Biology* **42**, 347–360.
- ROOSE, T. & FOWLER, A. C. (2004a). A model for water uptake by plants. *Journal of Theoretical Biology* **228**, 155–171.
- ROOSE, T. & FOWLER, A. C. (2004b). A mathematical model for water and nutrient uptake by roots. *Journal of Theoretical Biology* **228**, 173–184.

**Real-time, model-based control of pig growth.** D. J. PARSONS<sup>1</sup>, C. P. SCHOFIELD<sup>1</sup>, D. M. GREEN<sup>2</sup> AND C. T. WHITTEMORE<sup>3</sup>. <sup>1</sup>*Silsoe Research Institute, Wrest Park, Silsoe, Bedford MK45 4HS, UK*, <sup>2</sup>*Department of Zoology, University of Oxford, Oxford OX1 3PS, UK*, <sup>3</sup>*School of Geosciences, The University of Edinburgh, Agriculture Building, West Mains Road, Edinburgh EH9 3JG, UK*

Pigs of a commercial breed were reared in controlled environment facilities in 12 pens of 12 pigs. They were fed *ad libitum* diets that varied in protein content between pens, produced by blending two source diets.

Weight, estimated by visual image analysis, and feed intake were recorded for individual pigs each day.

The control system was based on a mechanistic growth model (Green & Whittemore 2003). Each week, two model parameters were optimized using the recorded data to improve the prediction of future growth. The parameters used were lean tissue growth rate and maintenance requirement for both energy and protein. The dietary blend for each pen, represented by a piecewise linear function, was then optimized to minimize the error from a target for weight or back-fat thickness. Several optimization methods were investigated: bounded quasi-Newton, nonlinear revised simplex and genetic algorithms (discrete and continuous). The best combination of speed, precision and robustness was achieved with the revised simplex method (Nelder & Mead 1965).

In one trial, weight gain targets of 50 kg and 60 kg over 70 days were set, using two pens for each target. In three of the four pens the final mean weight was within 2 kg of the target. In the fourth, unknown factors caused an interruption in the pigs' growth about 14 days from the end of the trial, having previously been on target. Single pens of pigs fed *ad libitum* on the low and high protein diets produced mean weight gains of 45 and 62 kg respectively. This trial has demonstrated the potential of the system to control the growth rate of pigs. A further trial has provided encouraging results for the control of back-fat depth.

This work was funded under the UK Defra LINK Sustainable Livestock Production Programme. The authors acknowledge the support of the sponsors: MLC, BOCM PAULS Ltd, PIC Ltd, and Osborne (Europe) Ltd. Experiments were conducted at ADAS Terrington, Norfolk.

- GREEN, D. M. & WHITTEMORE, C. T. (2003). Architecture of a harmonised model of the growing pig for the determination of dietary net energy and protein requirements and of excretions into the environment (IMS Pig). *Animal Science* **77**, 113–130.
- NELDER, J. A. & MEAD, R. (1965). A simplex method for function minimization. *Computer Journal* **7**, 308–313.

**The impact of cereal ideotype and planting row width on weed suppression in organic farming.** C. F. E.

TOPP<sup>1</sup>, D. H. K. DAVIES<sup>2</sup>, S. HOAD<sup>1</sup> AND P. MASKELL<sup>1</sup>. <sup>1</sup>*Research Division and* <sup>2</sup>*Consultancy Division, SAC, Edinburgh EH9 3JG, UK*

Weeds impact on the growth and development of cereal crops and hence on the yield and crop quality. The growth of weeds within the cereal crop is partially dependent on the light intercepted by both components, which is influenced by plant structure and management (Davies *et al.* 2002, 2004).

The model developed is based on Beer's law and explores the impact of management factors; namely, location of the site, drilling direction, row width, and crop morphology on light absorbed by the wheat

canopy and hence the potential for weed suppression. In essence, the canopy is described by inter-row spacing, width of the crop and crop height (Gizjen & Goudriaan 1989).

The model evaluates light interception at key stages of crop development, which have been identified as third leaf (GS 13-21), stem elongation (GS 31), ear emergence (GS 49), and flowering (GS 65). The important characteristics of the ideotype at the key stages are extinction coefficient, height of the plant and leaf area index.

The crop is sown in a north-south orientation with row spacings of 12, 17 or 24 cm. Typical data for an erectophile and planophile ideotypes at key growth stages have been tested in the model. The model confirms that at GS 13-21, morphology has little impact on the light intercepted by the crop. Nevertheless, until full canopy closure is established, row width has a major impact on light interception, and hence there is an interaction between crop morphology and row width. The results of the model suggest that planophiles intercept more light than erectophiles. Similarly, decreasing inter-row spacing reduces the likelihood of weed infestation. In addition, leaf area index has a major impact on the light intercepted by the canopy and hence on the potential for weed growth.

This work was funded by the EU (Contract EU-QLRT-1999-31418) and SEERAD. We would also like to thank David Bickerton and Alistair Drysdale from SAC, and the site farmer, Mr Andrew Stoddart.

DAVIES, D. H. K., HOAD, S., MASKELL, P. & TOPP, C. F. E. (2004). Looking at cereal varieties to help reduce weed control inputs. In *Proceedings of the Crop Protection in Northern Britain Conference 2004, Dundee*, pp. 159–164. Dundee: Association for Crop Protection in Northern Britain.

DAVIES, D. H. K., HOAD, S. & BOYD, L. (2002). WECOF: a new project developing enhanced weed control through improved crop and plant architecture. In *Proceedings of the UK Organic Research Conference 2002, Aberystwyth* (Ed J. Powell), pp. 299–302. Aberystwyth: Organic Centre Wales.

GIJZEN, H. & GOUDRIAAN, J. (1989). A flexible and explanatory model of light distribution and photosynthesis in row crops. *Agricultural and Forest Meteorology* **48**, 1–20.

**A conjoint model of grain water content and dry matter during grain development in wheat.** S. PEPLER, M. J. GOODING AND R. H. ELLIS. *Crops Research Unit, Department of Agriculture, The University of Reading, Earley Gate, Reading, Berkshire RG6 6AR, UK*

The filling of wheat grains, and grains of other cereals, with dry matter is intimately linked with the accumulation and subsequent loss of water by the grain. For example, in a review Borrás *et al.* (2004)

report that: maximum seed water content (ml/grain) has been used as an estimator of final seed volume and hence potential seed dry weight; the earlier maximum water content is achieved, the less able a genotype may be to modify its final seed weight in response to late changes in photosynthate availability; the period of initial increase in water content occurs at the same time as rapid endosperm cell division, and final endosperm cell number is also correlated with final grain weight of different genotypes; the end of grain filling with dry matter often occurs at the commencement of rapid net water loss from the grain; moisture content (% fresh weight) has been used to estimate the proportion of final seed dry matter that has been accumulated at intermediate stages of grain filling; and end of grain filling with dry matter usually occurs at about 40% moisture content irrespective of final seed dry weight. We propose, therefore, that grain dry matter and water dynamics should be modelled simultaneously in order to determine when grain filling has been completed. Based on the observations from many previous reports cited in Pepler *et al.* (2005), grain water content can be described by an initial linear increase with thermal time at rate  $a$  until thermal time  $m_1$ . Thereafter water content varies only slightly at rate  $b$  until  $m_2$ . After  $m_2$  water content declines rapidly at rate  $e$ . Grain dry weight is modelled as a linear increase at rate  $bgf$  until maximum grain dry weight ( $maxgf$ ) is attained at  $m_2$ . This model fits closely ( $r_{adj}^2$  97–99%) to weekly observations of grain in the field from different genotypes, sowing dates, spike positions, seasons and fungicide treatments (Pepler *et al.* 2005). These close fits require that observations before the lag phase of grain filling has ended (i.e. at about 150 °Cd after anthesis), or after moisture content has declined to 20%, are omitted. Using  $m_2$  in both the dry matter and water content parts of the model was justified by the data and greatly improved the ease of fit optimisation. It is possible that estimating  $m_2$  in this way gives a more accurate assessment of when grain dry mass maturity occurs, compared to estimating the end of grain filling from just dry matter data. The model produces new parameters that may help interpret genotype and environmental effects on grain filling, e.g.  $m_1$ . Water content can be calculated at  $m_1$ . Whether this water content is the maximum water content depends on whether  $b$  is positive or negative; when  $b$  is positive maximum water content can be calculated at  $m_2$ . Deriving moisture content from the model is straightforward.

BORRÁS, L., SLAFER, G. A. & OTEGUI, M. E. (2004). Seed dry weight response to source-sink manipulations in wheat, maize and soybean: a quantitative reappraisal. *Field Crops Research* **86**, 131–146.

PEPLER, S., GOODING, M. J. & ELLIS, R. H. (2005). Modelling simultaneously water content and dry matter dynamics of wheat grains. *Field Crops Research* (in press).

**An approach for the systematic simplification of models.** G. M. COX<sup>1</sup>, J. M. GIBBONS<sup>1</sup>, J. CRAIGON<sup>1</sup>, A. T. A. WOOD<sup>2</sup>, S. J. RAMSDEN<sup>1</sup> AND N. M. J. CROUT<sup>1</sup>. <sup>1</sup>*Division of Agricultural and Environmental Sciences, School of Biosciences, University of Nottingham, Sutton Bonington, Loughborough, Leicestershire LE12 5RD, UK,* <sup>2</sup>*Division of Statistics, School of Mathematical Sciences, University of Nottingham University Park, Nottingham NG7 2RD, UK*

The performances of models of complex agricultural systems are often assessed through some kind of “goodness-of-fit” measure (e.g. Residual Sum of Squares (RSS)). However, a model’s goodness-of-fit against a particular dataset can always be improved by the addition of more parameters, which may lead to over fitting and poor predictive performance. To avoid these pitfalls, modellers should follow the principle of parsimony (also known as Occam’s razor) and select models that are “as simple as possible, but no simpler”.

To assist the development of parsimonious models, several alternative model selection criteria have been developed in statistics and information science which balance goodness-of-fit measures with model complexity (e.g. Akaike’s Information Criterion (AIC) (Akaike 1973), Minimum Description Length (MDL) (Rissanen 1987), Bayesian Information Criterion (BIC) (Schwarz 1978), ICOMP (Bozdogan 2000)). However, these have rarely been applied to agricultural models in the literature.

Here we describe the development of a systematic approach towards the simplification of existing models using various selection criteria. To illustrate this approach, we present the results of the simplification of a radiocaesium plant-uptake model (Absalom *et al.* 2001). The model was simplified, by replacing model variables with constants, using five different criteria (RSS, AIC, BIC, MDL and ICOMP), and the generalizability of the resulting simplified models was assessed using an independent dataset derived from Nisbet *et al.* (1999). In each of the simplified models, the same three variables (pH,  $M_{CaMg}$  and  $CEC_{Humus}$ ) were replaced by constants, with a further two ( $Kd_{Humus}$  and  $RIP_{Clay}$ ) replaced in the model selected by BIC, MDL and ICOMP. The model selected by RSS and AIC was a better predictor of the parameterization dataset than the original model, suggesting that pH, which is an input variable, introduces noise into the system. The simplified models performed similarly against the independent dataset, and were better predictors than the original model.

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ABSALOM, J. P., YOUNG, S. D., CROUT, N. M. J., SANCHEZ, A., WRIGHT, S. M., SMOLDERS, E., NISBET, A. F. & GILLET, A. G. (2001). Predicting the transfer of radiocaesium from organic soils to plants using

soil characteristics. *Journal of Environmental Radioactivity* **52**, 31–43.

AKAIKE, H. (1973). Information theory and an extension of the maximum likelihood principle. In *Second International Symposium on Information Theory* (Eds N. Petrov & F. Csaki), p. 267. Akademiai Kiado: Budapest.

BOZDOGAN, H. (2000). Akaike’s information criterion and recent developments in information complexity. *Journal of Mathematical Psychology* **44**, 62–91.

NISBET, A. F., WOODMAN, R. F. M. & HAYLOCK, R. G. E. (1999). *Recommended soil-to-plant transfer factors for radiocaesium and radiostrontium for use in arable systems*. NRPB-R304. National Radiological Protection Board, Didcot, UK.

RISSANEN, J. (1987). Stochastic complexity and the MDL principle. *Econometric Reviews* **6**, 85–102.

SCHWARZ, G. (1978). Estimating the dimension of a model. *The Annals of Statistics* **6**, 461–464.

**The effect of diverse climates on the forecasting lead-time of crop simulation models.** C. LAWLESS AND M. A. SEMENOV. *Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK*

The interaction between weather and plant growth and development determines the final value of crop characteristics of interest (e.g. grain yield). As a plant’s lifecycle progresses from sowing towards maturity, the amount of uncertainty in the weather which the plant will experience during its complete lifecycle decreases. This reduction in uncertainty leads to increased accuracy in the prediction of crop characteristics.

In order to use crop simulation models for forecasting crop yield, for example, the weather which is used for simulation must be forecast in some sense also. Due to the non-linear response of crop simulation models to weather input, this weather forecast cannot simply be a single, best estimate of weather for the upcoming growing season, but must also incorporate the variability inherent in the climate (Porter & Semenov 1993).

To capture this variability, we used the LARS-WG weather generator (Semenov & Barrow 1997) to produce ensembles of weather data files which were a mixture of observed weather from a single site-year and stochastically generated (synthetic) weather specific to this site for the remainder of the growing season. The synthetic data are constrained to be a continuation of the preceding period of observed data, and satisfy a range of statistical tests when compared with historical data from the site.

To demonstrate the use of this method, for mixtures of observed and synthetic weather with increasing proportions of observed data, we used the crop simulation model Sirius (Jamieson *et al.* 1998) to produce distributions of final crop characteristics. Progressing through the plant lifecycle, as the proportion of synthetic weather in these ensembles decreased, the output distributions narrowed.

At some point the distributions became narrow enough to constitute accurate predictions. This point was defined as the forecasting lead-time for the simulation for a given site-year.

In this way, we have estimated Sirius's forecasting lead-time for several crop characteristics. By repeating the procedure for several years of observed historical data at a single site, we have produced cumulative distributions of forecasting lead-times. Using these distributions we analysed several European sites with diverse climates comparing Sirius's predictive capability at different geographic locations. We demonstrate that a site's climate has a significant effect on the forecasting lead-time of crop simulation models, placing a limit on the level of predictive accuracy fundamentally achievable by them.

Rothamsted Research receives grant-aided support from the BBSRC. This work was supported by a DEFRA funded project.

JAMIESON, P. D., SEMENOV, M. A., BROOKING, I. R. & FRANCIS, G. S. (1998). Sirius: a mechanistic model of wheat response to environmental variation. *European Journal of Agronomy* **8**, 161–179.

PORTER, J. R. & SEMENOV, M. A. (1993). The importance of non-linear responses in modelling the growth and development of plants. In *Predictability and Non-linear Modelling in Natural Sciences and Economics* (Eds J. Grasman & G. van Straten), pp. 151–171. Kluwer Academic: Dordrecht.

SEMENOV, M. A. & BARROW, E. M. (1997). Use of a stochastic weather generator in the development of climate change scenarios. *Climate Change* **35**, 297–414.

**Stabilization of polymorphism in gene-for-gene relationships.** A. TELLIER AND J. K. M. BROWN. *Department of Disease and Stress Biology, John Innes Centre, Norwich NR4 7UH, UK*

In the gene-for-gene relationship, plant defences are only effective when a resistance gene interacts with a specific avirulence gene in the parasite (Crute *et al.* 1997). A major challenge for theoreticians has been to account for the maintenance of genetic polymorphism in this system, for which there is much evidence from field and molecular data. Constitutive costs of resistance and virulence are the most obvious explanations, but evidence for high values of such costs is limited (Bergelson & Purrington 1996; but see Tian *et al.* 2003). In the absence of high costs, factors such as high mutation rates, restricted dispersal and interactions between multiple parasite species are required for polymorphism to be maintained (Damgaard 1999; Thrall & Burdon 2002).

We have developed a new theoretical framework to investigate gene-for-gene co-evolution. This predicts a general theoretical condition required to obtain stable polymorphism and enables links to be developed between theory and realistic situations in nature. A key development of previous theory is that host

plants may be attacked within one growing season by a succession of possibly different genotypes, virulent or avirulent, of a polycyclic parasite. The outcome of infection then depends strongly on competition within a host plant, on host-mediated reactions triggered by previous parasite genotypes, and on the shape of the function relating plant seed production to the number of successive parasite infections.

In this model, stable polymorphism, i.e. indefinite maintenance of resistant and susceptible plants as well as virulent and avirulent pathogens, is achieved with realistically small constitutive costs of gene-for-gene resistance and virulence. The stability of the polymorphic state also depends on the cost of resistance compared to the cost of disease. Finally, the relative importance for maintaining polymorphism of two different types of resistance can be determined: constitutive, gene-for-gene resistance, characterized by qualitative responses and very small costs, and inducible defences which are quantitatively effective and have a higher cost of expression. These conclusions emphasize the significance of interactions between parasites for gene-for-gene co-evolution.

BERGELSON, J. & PURRINGTON, C. B. (1996). Surveying patterns in the cost of resistance in plants. *American Naturalist* **148**, 536–558.

CRUTE, I. R., HOLUB, E. B. & BURDON, J. J. (1997). *The Gene-for-Gene Relationship in Plant-Parasite Interactions*. Wallingford: CABI Publishing.

DAMGAARD, C. (1999). Coevolution of a plant host-pathogen gene-for-gene system in a metapopulation model without cost of resistance or cost of virulence. *Journal of Theoretical Biology* **201**, 1–12.

THRALL, P. H. & BURDON, J. J. (2002). Evolution of gene-for-gene systems in metapopulations: the effect of spatial scale of host and pathogen dispersal. *Plant Pathology* **51**, 169–184.

TIAN, D., TRAW, M. B., CHEN, J. Q., KREITMAN, M. & BERGELSON, J. (2003). Fitness costs of R-gene-mediated resistance in *Arabidopsis thaliana*. *Nature* **423**, 74–77.

**Statistical modelling of weed seedbanks to consider the effect of crop rotations.** S. J. POWERS AND D. A. BOHAN. *Biomathematics and Bioinformatics Division, Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK*

To aid weed management policy at a time when agricultural practice must be adjusted to comply with measures for environmental stewardship farming, it is important to investigate the overall effect that the growing of particular crops in rotations has on the dynamics of weed seedbanks. This work shows that the relationship between successive numbers of weeds over years may be studied to develop models that can be used to give predictions for future populations, and that the variation in weed numbers may be explained by crop rotations which preceded the observation of the seedbank.

The models developed are for monocot, dicot and total weed data, taken from the seedbank database sampled during the Farm Scale Evaluations of genetically modified (GM) herbicide-tolerant crops (Champion *et al.* 2003; Heard *et al.* 2003). Here, only data from the non-GM, conventional cropping and herbicide management part of the trial on each farm are used. Weed seedbank observations were taken before (to give a baseline) and after cropping (i.e. a follow-up) from 66 spring-sown sugar beet, 59 spring maize, 67 spring oilseed rape and 65 winter oilseed rape field sites, sown over three years (2000–2002) split into four geographic regions (zones) of the UK.

Residual Maximum Likelihood (REML) developed by Patterson & Thompson (1971) and implemented in the GenStat™ (2004) statistical system was used to fit linear mixed models to the data set, accounting for zone and sowing year as random effects. For data on a log scale, the follow up seedbank was described by regression on the base line with adjustment for each of the four crops grown. Using factors with levels set up to identify previous crops grown on the sites, the baseline numbers were described by rotations of three years. These were amalgamated by management factors, sowing season (summer, winter, miscellaneous), type of crop (cereal, oilseed, vegetable, grass ley, set aside, miscellaneous) and target weeds (broadleaf, grass, miscellaneous, none) to give parsimonious models.

The application of statistical modelling here makes it possible to use current rotational policy to predict the weed seedbank levels as a key to investigating more environmentally sensitive crop rotations for future policy.

This work was funded by Defra and the Scottish Executive. Rothamsted Research receives grant-aided support from the BBSRC.

CHAMPION, G. T., MAY, M. J., BENNET, S., BROOKS, D. R., CLARK, S. J., DANIELS, R. E., FIRBANK, L. G., HAUGHTON, A. J., HAWES, C., HEARD, M. S., PERRY, J. N., RANDLE, Z., ROSSALL, M. J., ROTHERY, P., SKELLERN, M. P., SCOTT, R. J., SQUIRE, G. R. & THOMAS, M. R. (2003). Crop management and agronomic context of the Farm Scale Evaluations of genetically modified herbicide-tolerant crops. *Philosophical Transactions of the Royal Society of London series B* **358**(1439), 1801–1818.

GenStat™ (2004). *GenStat 7th Edition, GenStat Procedure Library, Release PL12.2*, Lawes Agricultural Trust, Rothamsted, Harpenden, UK.

HEARD, M. S., HAWES, C., CHAMPION, G. T., CLARK, S. J., FIRBANK, L. G., HAUGHTON, A. J., PARISH, A. M., PERRY, J. N., ROTHERY, P., SCOTT, R. J., SKELLERN, M. P., SQUIRE, G. R. & HILL, M. O. (2003). Weeds in fields with contrasting conventional and genetically modified herbicide-tolerant crops. I. Effects on abundance and diversity. *Philosophical Transactions of the Royal Society of London series B* **358**(1439), 1819–1832.

PATTERSON, H. D. & THOMPSON, R. (1971). Recovery of inter-block information when block-sizes are unequal. *Biometrika* **58**, 545–554.

**An integrated model of methane emissions from dairy cattle: responses at the herd level.** J. A. N. MILLS AND L. A. CROMPTON. *Animal Science Research Group, School of Agriculture, Policy and Development, The University of Reading, Whiteknights, PO Box 237, Reading, Berkshire RG6 6AR, UK*

A non-linear model of methane production from the dairy cow (Mills *et al.* 2003) was integrated into a new model of dairy herd dynamics with the objective of demonstrating the influence of herd reproductive management on whole herd methane emissions. The herd model was constructed in Visual Basic with discrete groups of animals split according to calving month. The herd model used an iterative procedure to calculate the number of animals calving, conceiving and being culled for each month over a five year period. Herd size was assumed to remain constant with newly calved heifers replacing those animals culled for failure to conceive or non-fertility reasons. Milk production was defined by predefined lactation curves for cows and heifers respectively. Herd milk output varied according to the length of lactation and the proportion of heifers in the herd. Methane emissions were calculated for each month of calving and subsequently the annual total was divided by the herd milk output in order to provide an index of methane production per litre of milk.

A sensitivity analysis for all year round calving herds demonstrated the effect on emissions of changing voluntary waiting period (VWP), conception rate (CR), and heat detection rate (HDR). Improvements in HDR were most effective at reducing emissions with a 5% reduction in methane output per litre of milk for every 10% improvement in HDR. However, the effect was non-linear with greater and lesser gradients below and above 50% HDR respectively. For seasonal calving herds VWP became increasingly important as the calving pattern became more condensed resulting in similar economies of methane production to those observed for HDR. Overall the model showed that there are clear environmental advantages to improvements in herd reproductive performance and that these can be achieved in parallel to direct economic gains to the producer. Lower emissions result primarily from the reduced animal numbers required to support a given level of milk production.

The financial support of DEFRA project LS3656 is gratefully acknowledged.

MILLS, J. A. N., KEBREAB, E., YATES, C. M., CROMPTON, L. A., CAMMELL, S. B., AGNEW, R. E. & FRANCE, J. (2003). Alternative approaches to predicting methane emissions from dairy cows. *Journal of Animal Science* **81**, 3141–3150.