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Evaluating soil fertility constraints on smallholder agriculture in semi-arid tropics

Project Leader

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Organisation

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Final Technical Report: Evaluating Soil Fertility Constraints on Smallholder Agriculture in the Semi-Arid Tropics (R5804)

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1. Executive Summary

Simulation models have become very well established in many areas of science and can be used as tools to disseminate the quantitative understanding of complex processes contained in the model. This is of particular importance for the development of resource-poor agriculture in semi-arid environments where many complex interacting factors limit crop production. Developing appropriate technologies to improve and sustain production will be performed predominantly by scientists working within NARS who will not generally have access to the full range of research resources available, for example, in international centres. A user-friendly model was perceived as a way to provide them with a tool which summarises current understanding of the factors limiting crop production.

Under earlier projects managed by NRI work was undertaken to develop a model (PARCH) for the water and light limited growth of sorghum, in the semi-arid tropics. The model was positively received, however the models lack of nutrient (N & P) sub-models was widely perceived as a limitation.

This project developed a series of sub-models for the simulation of soil nitrogen and phosphorus dynamics and crop responses to nutrient limitations. These have been included in the PARCH model. The nitrogen and soil organic matter sub-model is an extension of that developed by Jones & Kiniry (1986). The phosphate model has been constructed following the methods of Jones and co-workers (Jones et al, 1984a; Sharpley et al, 1984; Jones et al, 1984b); this description of phosphate dynamics was originally conceived as part of the EPIC model (Williams et al, 1983; Williams et al, 1984). Within each layer of the modelled soil profile the amount of nitrate and labile phosphorus is calculated and its uptake by the crop simulated.

The project has maintained close links with other related research (especially that managed by NRI), in particular considerable use has been made of the data and expertise developed in the Soil Fertility Project run by the University of Reading (Warren; managed by ODA). This project has provided data enabling the development and (limited) testing of the models for semi-arid low input situations.

The project has been successful in developing a model which simulates the growth of sorghum in semi-arid environments (with reasonable accuracy). In this respect the project's scientific objectives have been met. The level of success achieved with respect to the development objectives is harder to assess. NRI have undertaken several parallel projects to encourage dissemination and assess the take-up of the model. These have demonstrated considerable interest in the model, as well as a range of factors limiting its active and effective use. About 15 active users have been identified, together with a further 5 groups who intend to use the model in the future (G. Fry, pers comm.).

There are a number of issues which ODA should address when considering an extension of such work, these are outlined in this report.

2. Background

The use of simulation models has become very well established in many areas of science, especially agriculture and environmental science. They serve as very valuable tools to synthesise and test understanding of complex systems; in many cases the complexity can be so great that little progress is possible without the use of a model. In the case of this work we have attempted to go beyond this use of models as part of the research process, and provide the model as an output of the research. The PARCH model is a tool which helps to disseminate the quantitative understanding that it contains. This is of particular importance in the development of resource-poor agriculture in semi-arid environments where many complex interacting factors limit crop production. Moreover, developing appropriate technologies to improve and sustain production will necessarily have to be carried out at a local, or at best regional, scale and will have to based upon an understanding of the underlying processes. Such work will overwhelmingly be performed by scientists working within NARS who will not generally have access to the full range of research resources available in international centres. A user-friendly model was therefore perceived as a way to provide them with a tool which summarises current understanding of the factors limiting crop production.

Under earlier NRI managed projects work was undertaken to develop a model for the water and light-limited growth of sorghum in the semi-arid tropics. This model (PARCH) was intended to as user-friendly as possible and to focus on various (water) management factors that are the subject of research within ODA and NARS (for example water harvesting, weed control, control of soil evaporation). This latter feature was intended to provide a readily identifiable application which would encourage scientists unfamiliar with the use of crop models to recognise their utility. Throughout the project care was taken to minimise the user's requirement for computer hardware and expertise recognising that these can be limiting factors in developing countries. The functional outputs from this work were the model (made available on a single diskette) and a manual which described the use of the model. These were disseminated quite widely.

The model was positively received, in particular many users commented on its simplicity of use, especially when compared to models they had previously encountered. However the model's lack of nutrient sub-models was widely perceived as a limitation to its effective use within NARS. Moreover it was felt that these factors should be considered with particular reference to the problems of resource-poor agriculture where inputs would at best be limited.

3. Project Purpose

- To integrate consideration of nutrient deficiency into the PARCH model of crop growth in the Semi-Arid Tropics (which was developed under earlier projects managed by NRI).
- To ensure that methods and analysis approaches are available in a usable form to scientists working in National Research Networks.
- To test and validate the model at two sites in the semi-arid tropics.

4. RESEARCH ACTIVITIES

The principal activity within the project has been to extend the previously developed PARCH model to consider limitations to crop growth due to nitrogen and phosphorus deficiencies. The approaches adopted are outlined below.

4.1 Soil Nitrogen Model

4.1.1 Vertical Distribution of Nitrogen and Organic Matter

The model assumes that any mineral fertiliser applied before the crop is planted (or on the day the crop is planted) is uniformly distributed within the ploughlayer. In the case of fertiliser applied during the growing season it is initially distributed into the upper soil layer.

Any additions of organic fertilisers (i.e. manures) must take place before the crop is planted. This material is assumed to be distributed uniformly within the ploughlayer.

The initial soil humus, mineral nitrogen and soil organic matter (e.g. crop residues) are assumed to be uniformly distributed within the ploughlayer, and exponentially distributed below this layer. The exponential distribution parameter is set such that 1% of the nitrogen exists below a depth of ploughlayer+50cm.

$$\int_0^{z_p} N_{top} dz + \int_{z_p}^{z_p+50} N_{top} \exp(-k(z - z_p)dz = 0.99$$

Where

N_{top} is the concentration of soil mineral nitrogen (nitrate) in the plough layer (defined by the user)

Z_p is the plough layer depth (defined by the user)

4.1.2 Soil Organic Matter

Soil organic matter is divided into 5 pools, plus humus. These pools are used to simulate different rates of decomposition and have different potential rates of decomposition (table 1). When setting up the model it is necessary to specify the fraction of the soil organic matter, or manure addition, in each of these pools; possible values are suggested in the documentation.

Pool	1	2	3	4	5	Humus
Half-Life (d)	1	14	73	277	1264 (3.5 yr)	11550 (31.6 yr)

Table 1. Potential decomposition half-lives for the soil organic matter pools.

Within each soil layer the processes of soil organic matter decomposition, mineralisation of organic nitrogen and the immobilisation of mineral nitrogen are simulated each day. Nitrification is assumed to be non-rate limiting and is not included as a modelled process; mineralization therefore converts organic-N directly to nitrate.

The rate of change of available mineral nitrogen of layer i, $NO3^i$, is given by

$$\frac{dNO3^i}{dt} = (1 - F_{hum})M^i_{om} + M^i_{hum} - I^i$$

where:

F_{hum} is the fraction of nitrogen mineralised from fresh organic matter which is transferred to the soil humus pool (0.3).

M_{om} is the rate of mineralisation of nitrogen from the fresh soil organic matter (kg ha^{-1} layer^{-1})

M_{hum} is the rate of mineralisation of nitrogen from the soil humus (kg ha^{-1} layer^{-1}).

I is the rate of nitrogen immobilisation (kg ha^{-1} layer^{-1}).

The rate of mineralisation is calculated from the summation of the decomposition rates for the 5 pools (p=1,5) of fresh organic matter.

$$M^i_{om} = \sum_p D_p F^i_{Temp} F^i_{mois} F^i_{CN} N^i_p$$

where

N_p is the amount of nitrogen in pool p (kg ha^{-1} layer^{-1})

D_p is the potential decomposition rate for pool p (see table 4.1).

F_{Temp}, F_{mois}, and F_{CN} are zero to unity factors representing the limitation to decomposition due to temperature, soil moisture and C:N ratio respectively. The calculation of these is defined below.

The rate of mineralisation from the humus pool is calculated in a similar fashion to that of the fresh organic matter.

$$M^i_{hum} = D_{hum} F^i_{Temp} F^i_{mois} N^i_{hum}$$

where

N_{hum} is the amount of nitrogen in the humus pool (kg ha^{-1} layer^{-1})

D_{hum} is the potential decomposition rate for the humus pool (see table 1).

F_{Temp}, and F_{mois}, are zero to unity factors representing the limitation to decomposition due to temperature and soil moisture as in the calculation of organic matter mineralisation.

The rate of immobilisation of mineral nitrogen, I, is related to the rate of gornaic matter decomposition;

$$I^i = \text{Rate of Organic Matter Decomposition} \times \left(0.02 - \min\left(\frac{ON^i}{OM^i}, 0.02\right)\right)$$

$$= \left(\sum_p D_p F^i_{Temp} F^i_{mois} F^i_{CN} OM^i\right)\left(0.02 - \min\left(\frac{ON^i}{OM^i}, 0.02\right)\right)$$

where

ON^i is the amount of fresh organic nitrogen in layer i (kg ha^{-1} layer^{-1})

OM^i is the amount of fresh organic matter in layer i (kg ha^{-1} layer^{-1})

This relationship implies that immobilisation will occur if the C:N ratio of the fresh organic matter is greater than 20 (taking the proportion of carbon in fresh organic matter as 40%).

4.1.3 Temperature and Moisture Limitation

Soil temperature and moisture affect the rate of decomposition through the relationships shown in figs. 1 and 2 respectively.

Fig. 1. Relationship between the soil temperature decomposition limitation factor, F_{TEMP}, and soil temperature.

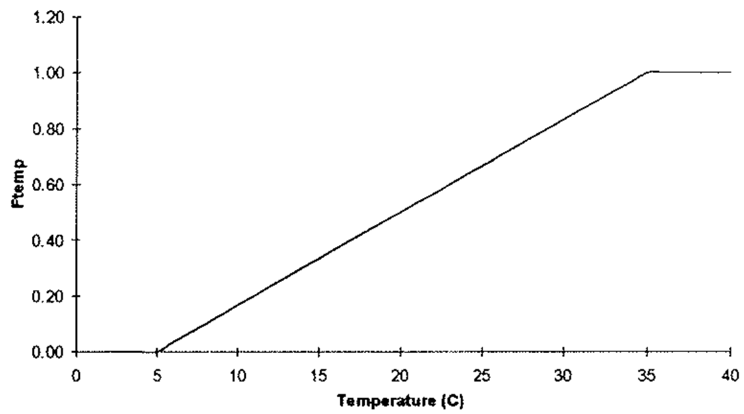
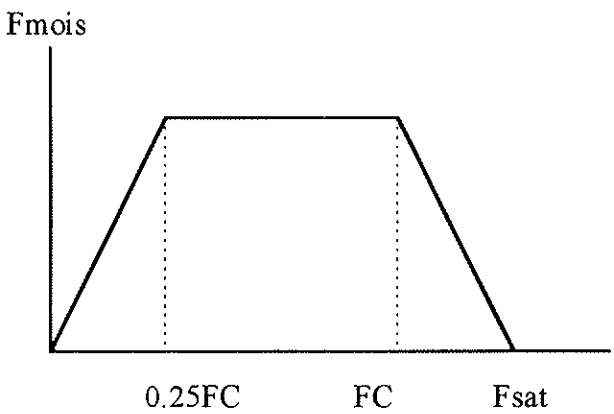


Fig. 2. Relationship between the soil moisture decomposition limitation factor, F_{MOIS}, and soil water content.



4.1.5 C:N Limitation

The rate of decomposition is affected by the C:N ratio of the system (CN) which is calculated for each layer as

$$CN = \frac{0.4 \times OM^i}{ON^i + NO3^i}$$

where

ON^i is the amount of fresh organic nitrogen in layer i (kg ha^{-1} layer^{-1})

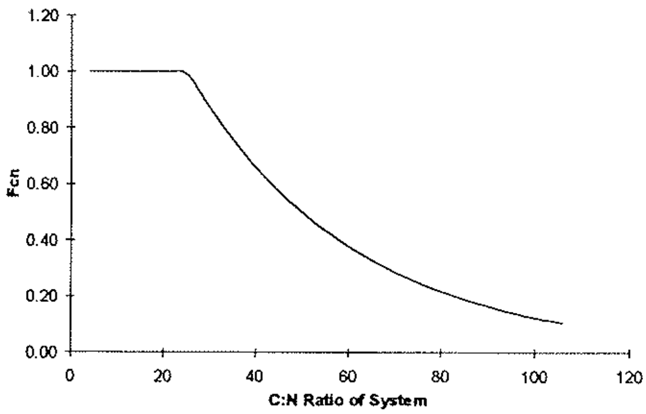
OM^i is the amount of fresh organic matter in layer i (kg ha^{-1} layer^{-1})

$NO3^i$ is the amount of mineral nitrogen in layer i (kg ha^{-1} layer^{-1})

The model assumes that above a C:N ratio of 25 the rate of decomposition is reduced exponentially with increasing C:N ratio as shown in fig. 3. The relationship is

$$F_{CN} = \exp\left(-0.693\frac{(CN-25)}{25}\right)$$

Fig. 3. The relationship between the CN decomposition limitation factor (F_{CN}) and the C:N ratio of the organic substrate.



4.2 Soil Phosphorus Model

4.2.1 Labile -P ⇔ Active-P

Within the soil, there are three inorganic-P reservoirs (P_L, P_A, P_S) intended to accommodate the dynamic transfer of P between pools of varying reactivity (labile ⇔active⇔stable). Organic-P forms include phosphate in humus, crop residues/manures and microbial biomass (P_H, P_R, P_M). Initial values of labile P (P_L) are given by the user as measured concentrations of topsoil Olsen-P **or** Bray-P from a data file. The distribution of P_L throughout the soil profile is then estimated following the method used to distribute Nitrogen with depth (section 4.1.1). Any inorganic fertiliser-P addition is immediately incorporated into the labile-P pool in the topsoil after units conversion from P_2O_5 to P. Movement of phosphate between *labile* and *active* pools is described as a specific daily increment, R_{LA} (kg ha^{-1} d^{-1}).

$$R_{LA} = K_{LA}\left[P_L - \left(\frac{F_B P_A}{1-F_B}\right)\right] F_W\, F_{TP}$$

where

K_{LA} is a rate constant, with a fixed value of 0.1 d^{-1}

F_W, F_{TP} are water and temperature factors which are defined below

F_B is the labile phosphate buffer factor, also defined below.

The water and temperature factors which limit R_{LA}, (F_W and F_{TP}), are calculated as:

$$F_W = \frac{\theta}{\theta_{fc}} \;;\; 0.0 < F_W < 1.0$$

where

θ is the volumetric water content of the soil layer

θ_{fc} is the volumetric water content of the soil layer at field capacity

The temperature factor F_{TP} is given by

$$F_{TP} = \exp(0.115\,T - 2.88);\; F_{TP} \text{ can exceed 1.0, when } T > 25° \text{ C.}$$

where

T is the soil layer temperature (C).

The labile phosphate buffer factor (F_B) is calculated from an empirical regression equation, depending on the soil type.

For calcareous soils:

$$F_B = -0.0061\,(\%CaCO_3) + 0.58$$

where

%CaCO3 is concentration of calcium carbonate in the soil (as a %), entered by the user.

For *slightly* weathered soils (dominated by 2:1 aluminosilicate clay mineralogy):

$$F_B = 0.0043(\%BS) + 0.0034\,P_L + 0.11\,pH - 0.70$$

where

%BS is the percentage of the soil cation exchange capacity which is occupied by base cations (e.g. Calcium), entered by the user.

pH is the soil pH, entered by the user.

For highly weathered soils (significant sesquioxide and kaolinitic mineralogy):

$$F_B = -0.047\ln(\%Clay) + 0.0045 P_L - 0.053(\%C) + 0.39$$

where

%Clay is the soil clay fraction (as a %), supplied by the user.

%C is the soil organic carbon concentration (as a %), calculated from data supplied by the user.

The initial concentration of active P (P_A) is calculated from the labile phosphate buffer factor (F_B).

$$P_A = P_L\left(\frac{1-F_B}{F_B}\right)$$

4.2.2 Active-P ⇔ Stable-P

At equilibrium, and for the initial set-up conditions, the ratio $P_S : P_A$ is assumed to be 4 : 1. Otherwise, transfer of phosphate-P between the *active* (P_A) and *stable* (P_S) pools is also calculated as a specific daily increment (R_{AS}, kg ha^{-1} d^{-1})

$$R_{AS} = K_{AS}(4P_A - P_S)$$

where K_{AS} is a rate coefficient (d^{-1}), whose calculation is defined below.

In calcareous soils the rate coefficient K_{AS} is constant,

$$K_{AS} = 0.00076\ \mathrm{d}^{-1}$$

whereas in non-calcareous soils, K_{AS} (d^{-1}) is a function of the labile phosphate buffer factor, F_B,

$$K_{AS} = \exp(-1.77 F_B - 7.05)$$

4.2.3 Mineralization of organic-P: $P_R \Rightarrow P_L$; $P_H \Rightarrow P_L$

Mineralization of P from crop residues and from soil humus is calculated from the simulated organic matter decomposition and the known P content of each substrate (P_H and P_R). The phosphate concentration in added manure and/or crop residues (P_R) must be given by the user in the form of a C:P ratio. The concentration of humus-P (P_H) is calculated on the basis of an organic-N to organic-P ratio of 1 : 0.1464; the distribution of humus-N is described in section 1.1. It is assumed that 80% of the P released from the mineralization of P_R contributes to the P_L pool and 20% is incorporated into soil humus (P_H).

4.2.4 Immobilization of P by crop residues: $P_L \Rightarrow P_R$

The calculation of organic residue decomposition rate, R_R, is based on the rate of nitrogen mineralisation (given the C:N ratio) (section 4.1.2). The corresponding rate of labile P immobilization (R_{LR}) depends on the phosphate status of the microbial biomass, estimated from the concentration of labile P.

$$R_{LR} = 0.16\, R_R \left(\frac{P_M}{W_M}\right)$$

where the ratio P_M/W_M is dependent upon P_L

$$\frac{P_M}{W_M} = 0.02 \qquad P_L > 10kgha^{-1}$$

$$\frac{P_M}{W_M} = 0.01 + 0.001P_L \qquad P_L \geq 10kgha^{-1}$$

4.3 Nutrient Uptake

4.3.1 Uptake of Nitrogen

The uptake of nitrogen from the soil by the roots is calculated for each soil layer within the model. It is dependent upon the concentration of nitrate within the layer, the root density, the water content and the nutrient stress of the crop.

For each layer the nitrogen uptake for a crop at optimal nitrogen status, U_N^i, is given by,

$$U_N^i = 0.07\left((1-\exp(-0.09[NO3^i])\right)\sqrt{\frac{\rho^i}{0.25\rho_{\max}}}\,\frac{aw^i}{0.5\sqrt{aw_{fc}^2}}\left(1+\sigma_N\right)$$

where: $[NO3^i]$ is the nitrate concentration in the layer i.

ρ^i is the root length density in the layer i.

ρ_{max} is the maximum root length density.

aw^i is the available water in layer i.

aw_{fc} is the available water when the soil is at field capacity.

σ_N is the crops nutrient stress (an index between 0 and 1)

Total optimal nitrogen uptake, U_N^O, is the summation over all layers of U_N^i i

$$U_N^O = \sum_i U_N^i$$

This rate of uptake is further adjusted depending upon the nitrogen status of the crop. This is defined in terms of a critical nitrogen concentration below which the crop is nitrogen limited. For the roots the critical **N** concentration, $[NCrit_{root}]$ is a constant (0.0106 gN gDW^{-1}). In the case of the above ground parts the critical concentration, $[NCrit_{Tops}]$ depends on the thermal age of the crop relative to the thermal requirement for maturity.

$$[NCrit_{tops}] = 0.01\exp(1.52 - 1.6Xstage)$$

$$Xstage = \frac{\Theta}{(\Theta_{GS1} + \Theta_{GS2} + \Theta_{GS3})}$$

where: Θ is the thermal time the crop has accumulated above base temperature

$\Theta_{GS1}+\Theta_{GS2}+\Theta_{GS3}$ is the total thermal time required to reach maturity.

A minimum nitrogen concentration is also defined, below which crop growth will cease completely, $[Nmin_{tops}]$.

$$[Nmin_{tops}] = 0.0125 - 0.002Xstage \qquad Xstage < 0.4$$

$$[Nmin_{tops}] = 0.045 \qquad Xstage \geq 0.4$$

The root and shoot demand for nitrogen is calculated from the biomass and the difference between the crop's nitrogen concentration and the critical nitrogen concentration, adjusted to allow for potential luxury uptake of nitrogen.

$$Ndemand_{tops} = (ADW - WG)([Ncrit_{tops}] \times luxury - [N_{tops}])$$

$$Ndemand_{roots} = (WR)([Ncrit_{roots}] \times luxury - [N_{roots}])$$

where: $Ndemand_{tops}$ is the nitrogen demand of the shoots.

$Ndemand_{roots}$ is the nitrogen demand of the roots

ADW is the total crop above ground dry weight.

WG is the total weight of grain

WR is the weight of roots.

luxury is a factor representing the extent of luxury nitrogen uptake (1.5).

The crop uptake of nitrogen, U_N, is then calculated as

$$U_N = (Ndemand_{tops} + Ndemand_{roots})U_N^O$$

This amount of nitrogen is debited from the soil profile layers as appropriate.

The overall crop nitrogen status in then determined by a factor, F_N, which is given by

$$F_N = 1 - \frac{[Ncrit_{tops}] - [N_{tops}]}{[Ncrit_{tops}] - [Nmin_{tops}]}$$

where:

[Ntops] is the concentration of nitrogen in the above ground parts of the crop (excluding grain).

When $F_N<1$ the crop is below its optimum nitrogen concentration and photosynthesis will be nitrogen limited. However this doesn't necessarily imply that nitrogen is the most limiting resource. Either water, temperature, or phosphorus could be more limiting. Nutrient stress, σ_N, is calculated directly from F_N.

4.3.2 Uptake of Phosphorus

Plant uptake of phosphate is calculated from the (sub-optimum) plant P concentration, the daily growth increment, labile phosphate availability and limiting factors related to root density and soil water content. The daily increment describing P transfer from the soil labile pool to the crop (R_{LC}) is given below. The potential rate of P assimilation is assumed to be 1.5 times that required to maintain the optimum plant-P concentration.

$$R_{LC} = 1.5\, G \left(\frac{P_C^{\,opt}}{W} \right) \min(F_R, F_W, F_C)$$

The phosphate availability factor (F_C) is calculated from the current labile P concentration, expressed as (converted to) units of mg P kg^{-1} soil.

$$F_C = \frac{P_L}{20} \quad ; \quad P_L < 20\ mg\ kg^{-1}$$

$$F_C = 1.0 \quad ; \quad P_L > 20\ mg\ kg^{-1}$$

The optimum P concentration in the crop depends on the current growth stage (Xstage).

$$\left(\frac{P_C^{\,opt}}{W} \right) = 0.00684 - 0.00108[XStage] \quad ; \quad XStage < 0.4$$

$$\left(\frac{P_C^{\,opt}}{W} \right) = 0.00238 - 0.000056[XStage] \quad ; \quad XStage \geq 0.4$$

Phosphate deficiency affects the crop growth rate through a stress factor (F_{PC}), which is calculated from the extent to which the crop P concentration falls below the optimum value (P_C/P_C^{opt}).

$$F_{PC} = 1 - \left(\frac{F_P}{F_P + \exp(3.38 - 10.9 F_P)} \right)$$

The scaling factor F_P is calculated from:

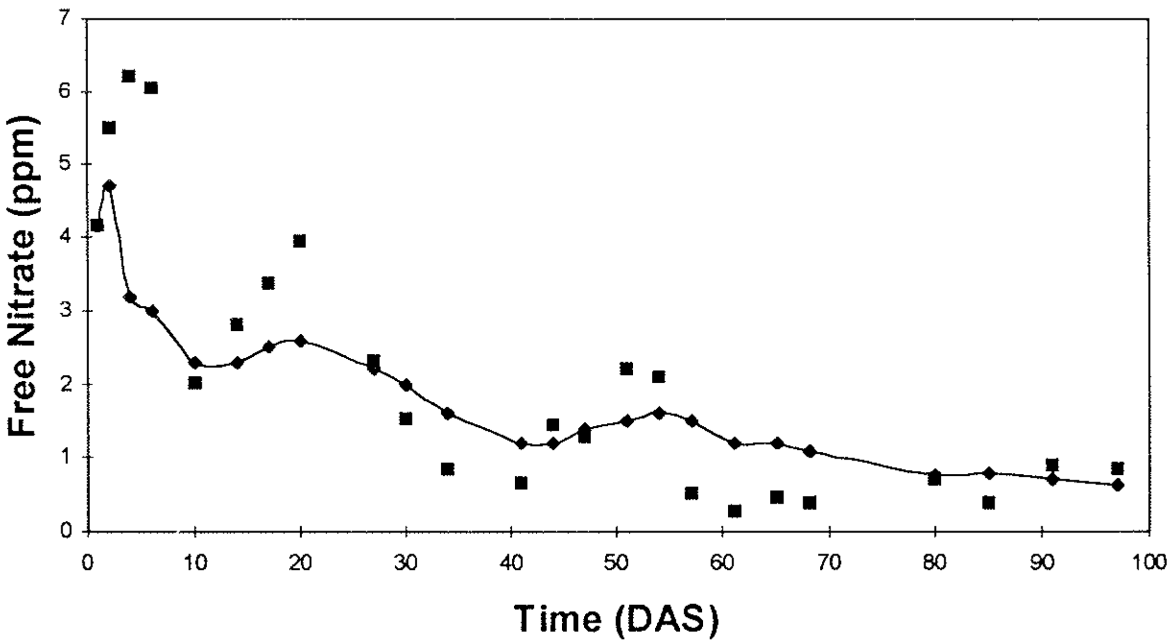
$$F_P = 2.0 \left(1 - \frac{P_C}{P_C^{\,opt}} \right)$$

Nutrient stress, σ_N, is calculated directly from F_P.

4.4 Results

Limited data is available to test these models in appropriate environments. The phosphorus model is essentially untested, although qualitative tests have been undertaken using the Reading data. However the model is based upon the best available approaches in the literature and has been 'expert-tested' to ensure that the results are reasonable over a range of conditions. Further testing will take place, over the next 3 years in a joint project based at IACR Rothamsted intended to optimise phosphate nutrition of maize in Kenya. The nitrogen sub-model has been tested more thoroughly using field data from Australia and Kenya. The Kenya data is of particular value as it has enabled a test of the soil organic matter decomposition aspects of the model. This data was provided by the Reading Soil Fertility Project (G. Warren, pers comm) and comprised soil, weather and crop information. Fig. 5. shows an example of the results obtained for one site where nitrate concentrations were measured throughout the cropping season. The agreement is satisfactory although the model does not show the distinct peaks and troughs of the observed data.

Fig. 5. Comparison between simulated and observed nitrate concentration in topsoil at the Machanga site (Kenya).



Outputs

The principal project output is the PARCH model. This is available as a menu-driven program for use on PCs and is supplied on diskette. The software is supported by a comprehensive three volume user manual (developed in collaboration with Cranfield University) which describes the theory, testing and use of the model. A 'workbook' which illustrates the application of the model is included as part of the documentation. These, together with other publications, are indicated below.

Contribution of Outputs

PARCH will contribute to ODA development objectives by providing scientists working within NARS with a tool which effectively summarises the factors which limit crop production in the semi-arid tropics. This can be used to assist in the development, planning, execution and analysis of research intended to develop appropriate (local) technologies to increase and sustain crop production.

The model has previously been supplied to anyone requesting it directly. Moreover, through related projects organised by NRI, efforts have been made to disseminate the model to interested parties in Africa. These have received technical support from Nottingham and have reported separately. The new model will be disseminated to everyone who already has a copy of the earlier version; formal input from Nottingham will then cease as we are not resourced for ongoing support of the model. However, aspects of PARCH have been incorporated into the agroforestry model HYPAR and ODA funded work on this is continuing under the co-ordination of ITE. As a further route for dissemination NRI may like to consider placing information about PARCH on their World-Wide-Web site. Potential users could perhaps access the model and documentation directly from there.

The development of models such as PARCH is potentially open-ended. There remain many areas where scientific questions are unanswered. However in terms of contributing to the overall programme goal the limiting factor is not the availability or utility of the model but its take-up within National Agricultural Research Networks. The additional dissemination efforts mentioned above have highlighted that there is considerable enthusiasm for the model (and is in use in 15 centres), however there are a range of factors which limit its use in NARS. These should be considered before further work is undertaken.

Moreover, if further modelling work were to be funded by ODA in the future, formal collaboration and integration with other modelling systems developed elsewhere should be considered,. in particular the DSSAT and APSIM. These had undergone little or no development when the PARCH work commenced but are now very advanced. In the case of DSSAT there now exists a well established user community. However, the case is not clear-cut as some PARCH users have chosen PARCH in preference to the DSSAT system because of PARCH's greater usability. APSIM is more commercially based and there are considerable costs involved in its use, although (from the author's limited knowledge) it is not based upon increasingly obsolete computing systems.

As discussed earlier, the use of simulation models has become very well established in many areas of science, especially agriculture and environmental science. It is likely that ODA will wish to fund further modelling work across a range of subject areas. However there can be considerable software costs involved. 'Custom-made' systems such as PARCH (or indeed DSSAT or APSIM) are expensive to develop and without ongoing development quickly become obsolete in computing terms. Whilst this may not restrict their functional use it may limit their takeup in the future. For example both PARCH and DSSAT are DOS programs, they do not use the standard commands and procedures used with WINDOWS programs, such as EXCEL, which almost every scientist now uses. ODA should be aware that there are a number of commercially available modelling packages (in the £300-500 range) and it may be more appropriate to encourage researchers to use these. Within

Environmental Science at Nottingham the package Modelmaker is extensively used for a wide range of work (Cherwell Scientific Publishing Ltd) and has almost completely replaced the development of custom-made programs. There is considerable development in this area and, of course, the costs are shared over very large numbers of users.

Publications:

Describing the use of PARCH in Agroforestry Research:

Lawson, G.J., Crout, N.M.J., Levy, P.E., Mobbs, D.C., Wallace, J.S., Cannell, M.G.R., & Bradley, R.G. (1995). Representing the tree-crop interface with coupled forest and crop process-models. Agroforestry Systems **30**:199-221.

Lawson, G.J., Cannell, M.G.R., Crout, N.M.J., Dewar, R.C., Levy, P.E., Mobbs, D.C., Robertson, W.H. (1994). Agroforestry modelling and coordination. Agroforestry Forum **5**(2), 63-65.

Describing aspects of the PARCH model:

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In addition two further papers have been submitted to the Journal of Agricultural Science and we are currently considering the referees comments.

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