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An evaluation of uptake and developmental impact in the semi-arid tropics of four crop production models

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SUMMARY

In the last two decades, crop production models have been developed or modified for use in the semi-arid tropics. Although potential uses of crop models have been discussed in detail in the literature, examples of successful uptake and impact of those models is lacking. Four models developed specifically for the semi-arid tropics were used as a basis for evaluating uptake and impact of models in the semi-arid tropics. PARCH accounts for differences in water availability when predicting yield. PARCHED-THIRST covers water-harvesting, run-off and run-on. EMERGE identifies opportunities for successful crop establishment, and SWEAT calculates evapo-transpiration and estimates temperature and moisture throughout the soil profile. The models are dynamic, deterministic and mechanistic in nature. The equations and notations comprising them are generally well structured, meaningful and concise. The uptake and impact of these models on crop production in the semi-arid tropics was assessed using questionnaires and semi-structured interviews with the model developers. There was limited uptake. Low uptake resulted from lack of efficient dissemination and discontinuity in information transfer: from model developers to scientists in the national research institutions; and thereon to extension agents and so to farmers. Although this paper is based on a study of only four models, there are important lessons to be drawn in order to avoid similar mistakes being repeated. Guidelines for improving impact for future crop production modelling projects are proposed.

INTRODUCTION

Crop simulation modelling in agriculture can have potential advantages for researchers, advisors and farmers. Monteith (1996) noted that although there are numerous papers on construction of models in the literature, examples of successful uptake and impact are rare. In the semi-arid tropics, such examples are even more scarce. Given that the UK government aid policy targets the elimination of poverty in poorer countries through the promotion of sustainable development (Warham 1998), it is timely to ask if investment in simulation modelling has contributed to that objective. Evaluation of four models funded by the United Kingdom's Department for International Development (DFID) was used as a basis for assessing developmental impact from such models.

In the late 1980s, modelling was considered appropriate to use in the study of semi-arid crop production systems, and development of models began in order to simulate growth, runoff, evaporation from soil, and emergence and establishment in these environments (Crout & Azam-Ali 1990). Due to varied constraints present in semi-arid production systems, four models were developed and continue to be developed to address the effects of water limitation, water harvesting techniques, evapo-transpiration and seedling establishment. The models, referred to as 'PARCH Suite', were managed by Natural Resources International and were intended to complement each other. PARCH (Predicting Arable Resource Capture in Hostile Environments) (Crout *et al*. 1997) simulates the growth and development of sorghum and millet (and to some extent maize) in response to different weather and soil conditions. PARCHED-THIRST (Predicting Arable Resource Capture in Hostile Environments During the Harvesting of Incident Rainfall in the Semi-Arid Tropics) (Young & Gowing 1996), was developed to evaluate water-harvesting techniques for maize in Tanzania and it is an updated version of the PARCH model. EMERGE (Mullins *et al*. 1996) simulates emergence patterns of sorghum in Tanzania. SWEAT (Soil Water Energy and Transpiration) (Daamen & Simmonds 1994; Daamen *et al*. 1995; Daamen 1997) was developed to simulate evapo-transpiration from sparse canopies of pearl millet in Niger.

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Uptake of the outputs of research can be by intermediate or end users (Garforth & Usher 1997). Farmers, as the end users of agricultural research outputs, are unlikely to use crop simulation models directly. This is particularly the case in the semi-arid tropics where the small scale of farming, low incomes, poor communications and lack of computing infrastructure combine to make models inaccessible to farmers. The impact of models on poverty and on the sustainability of livelihoods will therefore be indirect, through uptake and use in the work of researchers or extensionists. Possible pathways to impact are through consultants who might use them to generate farm-specific advice; through extension organizations which provide general recommendations or information to support the decision making of farmers within a particular set of environmental parameters; and through researchers who might use them to narrow down the focus of research and speed up the generation and evaluation of technology which will increase production or reduce risk. In fact, given the lack of computing facilities and expertise within extension organizations in the semi-arid tropics, the main users are likely to be researchers.

Over one million pounds was spent by DFID for developing the above listed models. The objectives of this paper were (a) to evaluate the uptake and practical use of the four models in the semi-arid tropics, (b) based on the findings, to suggest ways of improving uptake of models in general, and (c) question the current methods by which modelling projects are funded.

MATERIALS AND METHODS

Methodology

Project documentation from research proposals to final technical reports was provided by research managers of DFID's Natural Resources Systems Programme at Natural Resources International Ltd. Additional information was obtained through semi-structured interviews with the principal investigators and other project staff. Where present, publications in conference proceedings and refereed journals were also used as a source of information.

Questionnaires were prepared and sent to model users, mainly in the semi-arid tropics, to collect information on the use of the models both by individuals and the institutions they represent. Lists of potential users of three of the models were compiled from information provided by the model developers or from their research reports. However, no such information was available for SWEAT and the model developers believed that there was limited uptake by agricultural scientists in the tropics. Of the 165 questionnaires sent out, only 27 were completed and returned. There was an overlap in the lists: the 27 responses were from 16 respondents. One of these, an agricultural economist, was a lecturer in a higher education institution. The remainder were staff of research institutes. They comprised six agronomists, three agricultural engineers, a plant physiologist, an agrometeorologist, a biometrician, a livestock specialist and a plant breeder. It is reasonable to assume that those who responded are the ones with greatest interest in models and their application.

Summary of projects and brief model descriptions

Few details of these four models have previously appeared in the mainstream literature, so a brief account of each model now follows.

PARCH

The PARCH model was developed from 1990–96 and uses a daily time step to simulate crop growth. On each day, the light and water are captured and converted into assimilated dry matter. This is calculated following the methodology within PARCH's pre-cursor model RESCAP (Monteith *et al.* 1989). Depending upon the availability of these resources, and the crop's ability to capture them, crop growth is considered as either light or water limited. An index of stress is calculated in terms of the ratio of light- (incident radiation intercepted) to water-limited photosynthesis. This stress index is used to control a number of the crop's stress responses, such as leaf rolling or increased partitioning to roots (Crout *et al.* 1997; Hess *et al.* 1997; Stephens *et al.* 1997).

Crop water balance simulation is a key component of PARCH. The water use efficiency parameter links the water demand calculated from the potential dry matter production (driven by intercepted solar radiation) with the water uptake by the crop and is crucial to the correct prediction of final dry matter production and yield (Hess & Stephens 1994).

PARCHED-THIRST

Development of the PARCHED-THIRST model started in 1992 and the first phase terminated in 1996. A second phase finished at the end of 1999. PARCHED-THIRST was developed to simulate the key processes influencing the performance of rainwater harvesting systems and uses the PARCH model in order to predict yields. Rainwater harvesting is defined as the collection of run-off as sheet flow from an adjacent catchment area into a cropped area without storage other than in the cropped area (Young & Gowing 1996). In other words, the model assumes that there are two distinct areas of the field in which one part is a catchment (run-off) area and the other a cropped (run-on) area.

PARCHED-THIRST uses daily rainfall and other agro-meteorological data. It includes a stochastic

Weather Generator for extension of historical data to provide simulation of long-term performance. Daily rainfall values are then converted by the rainfall disaggregator into intensity data (i.e. mm rain for each hour) which are required by the infiltration model. The rainfall–run-off process is simulated as an infiltration excess (for the duration of the simulation) with infiltration being determined by the Green and Ampt infiltration calculator. The modified PARCH model adds soil-water redistribution and crop growth simulation routines to PARCHED-THIRST which complete the system (Young & Gowing 1996).

Currently, a modification of the pedotransfer functions submodel is underway (van der Meer & Twomlow, unpublished). The new submodel will enable PARCH-THIRST to allow for weed competition which is a major problem in semi-arid production systems.

SWEAT

The SWEAT model was developed from 1991–95 and simulates detailed diurnal time courses of evaporation processes from the soil surface or from the canopy, and the water or temperature status of the soil close to the soil surface. Although the model also simulates the effect of root water uptake and transpiration from a sparse canopy, vegetation was not considered (Daamen & Simmonds 1994).

SWEAT uses hourly data of air temperature, humidity, windspeed and radiation. It requires information about the soil (texture, water retention and hydraulic conductivity) and, if present, the crop (height, leaf area index and distribution of root length density). The SWEAT model simulates a one-dimensional soil profile by considering the soil as a series of homogeneous layers with variable thicknesses (Daamen & Simmonds 1994).

EMERGE

The EMERGE model and associated research was conducted in 1992–96. EMERGE was developed to simulate the germination, seedling growth, emergence, and establishment of a population of seeds as a function of soil physical conditions.

EMERGE consists of two parts: SWEAT (described above) and GEMA, a model that uses the soil temperature and matric potential predicted from SWEAT to estimate duration from sowing to germination, shoot growth, and emergence for a population of 100 seeds.

GEMA calculates the seed mass lost by respiration after germination had begun. If the seed takes too long to emerge, it may fail because the seed runs out of its reserves. Both soil hardening and soil drying can thus result in failed emergence, as can a lethal soil temperature at the shoot meristem (Mullins *et al.* 1996).

RESULTS

The PARCH suite of models as a whole are dynamic, deterministic and mechanistic. The equations and notations were presented in a structured, meaningful and concise manner. Evaluation of technical aspects of the performance of the models was not attempted because the focus of the paper is on the uptake and impact of those models. Model verifications have been carried out for PARCH in Kenya (Hess & Stephens 1994), PARCHED-THIRST in Tanzania (Hatibu *et al.* 1997), SWEAT in Niger and India (Daamen & Simonds 1996) and EMERGE in Pakistan (Mullins, unpublished).

Evaluation of uptake and impact

PARCH

Ninety-eight questionnaires were sent out to PARCH users (Fig. 1) mainly in Tanzania, Kenya, Malawi, Zimbabwe and Botswana.

Out of the 16 people that replied (Fig. 1), five found it useful in their work, one found it difficult to use, six had looked at it only briefly, and the remaining four had not used the model at all. Those who used PARCH did so for educational purposes and to analyse experiments. They found it particularly useful for modelling yield and, to a lesser extent, for determining the time of planting and methods of reducing evaporation from soil.

Difficulty in calibrating PARCH to the local climate, soil and crop conditions was the major problem faced by potential users, followed by lack of understanding of how the program works, unavailability of documented examples on use of PARCH, and problems in obtaining meteorological data in the format required by the model. Contrary to common assumptions, the availability of computers was the least concern among users.

Establishment of a technical support facility (by email, fax, etc.) and training (or a workshop) on the use of PARCH were cited as urgently required. Practical demonstration of experiments from their region and formation of a users' group were also noted as being useful.

The major agronomic constraint to crop production cited by all respondents was water (drought). Soil fertility, particularly low levels of nitrogen, and lack of adequate facilities for conducting research were also mentioned as limiting factors.

The reasons cited for not using PARCH in the future were preference for other models (e.g. with a better user interface), not relevant to current research priorities, and a policy of some institutions to use models developed in-house or collaboratively.

PARCHED-THIRST

Information on users of the PARCHED-THIRST

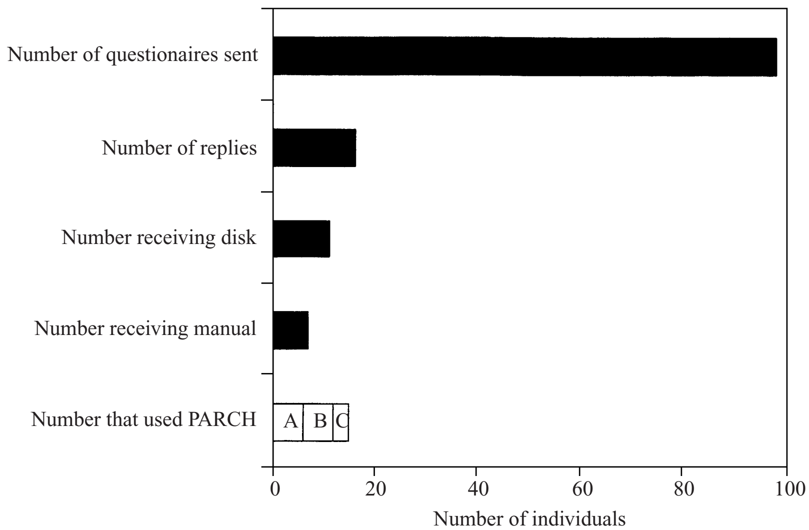

Fig. 1. Summary of the response to questionnaires sent to users of the PARCH model. The letters A, B, C represent number of individuals who used PARCH briefly, are continuing to use it, and intend to use PARCH, respectively.

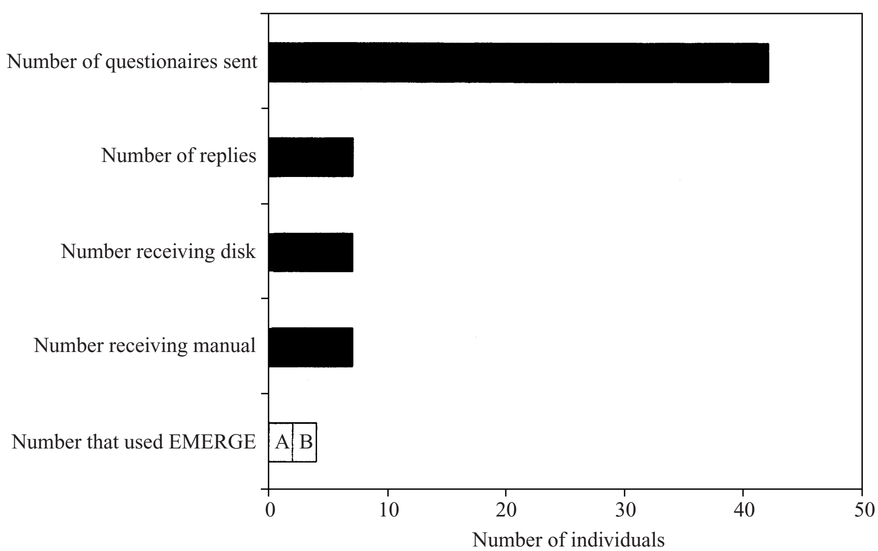

Fig. 2. Summary of the response to questionnaires sent to users of the EMERGE model. The letters A and B represent number of individuals who used EMERGE briefly and are intending to use EMERGE, respectively.

model was difficult to obtain. Questionnaires were sent to 22 individuals mainly in Kenya and Tanzania, of whom only three replied. All three respondents found the model useful in modelling yield and evaporation from soil but they reported difficulties in calibrating it to their climate, soil and crop conditions. This limited their use of the model. The two respondents from the semi-arid tropics found a lack of examples of the use of the model in the literature, and found the availability of soil and meteorological data to be limiting. The other respondent (from the UK) found no limitation to the use of the model.

SWEAT and EMERGE

No records of SWEAT model users in the semi-arid tropics were obtained. Forty-five questionnaires were sent to EMERGE users (Fig. 2) mainly in Australia, India, Tanzania and the UK.

Although a similar proportion of EMERGE and PARCH users replied to the questionnaires, the respondents did not use EMERGE as much. In fact, most had only been involved in the development of the model. Only two individuals actually used it. They found it useful in modelling the number of emerged plants and studying methods of reducing evaporation from soil. EMERGE was also used for comparison of output from other models (e.g. SUCROS). No comment was made on any constraints in using the model, or improvements that would make EMERGE more effective.

DISCUSSION

The results clearly show limited uptake of the models. Low uptake is not restricted to these four models. Boote *et al*. (1996) stated that, despite the potential of crop growth models in research, management and policy decisions, farmers and advisors have made little use of crop models. A recent effort to collect examples of developmental impact of models among a group of agricultural modellers over the internet came up with almost no examples (Robin Matthews, unpublished). Parker (1999) also recorded similar problems of developmental impact of models in the UK. Two questions follow: what were the causes of low uptake? and how can uptake be improved? The causes for low uptake can be grouped into (a) technical aspects of the models and (b) dissemination methods.

Some users of the PARCH model found it difficult to provide meteorological data in a format required by the model. The input and output file formats need to be standardized so that common spreadsheet packages such as Microsoft Excel can be used. PARCH requires numerous parameters to describe the agronomic characteristics of a cultivar. Due to the large number of cultivars used in the semi-arid tropics, these are difficult to estimate for each cultivar. Either the most common cultivars need to be available as options or fewer parameter values need to be required to describe a cultivar.

The PARCHED-THIRST model solved some of the technical problems of PARCH (e.g. Microsoft Windows interface, easy to use file formats, etc.). However, lack of a nutrient cycling submodel and the assumption of complete crop emergence might have contributed to the low uptake of the model. Its developers are working to add a decision support facility to the model (Gowing, unpublished). This, together with the weed competition submodel currently being developed, should give PARCHED-THIRST a better chance of having an impact in the semi-arid tropics.

The lack of uptake of the SWEAT model by agricultural scientists was most probably due to its requirement for hourly meteorological data. These data are extremely difficult to obtain in the semi-arid tropics and will continue to be a major limiting factor in the future. However, a submodel could be developed at a relatively low cost to disaggregate daily rainfall and temperature data into hourly data. The new submodel would need to be tested and evaluated against results from field experiments and model predictions from the original SWEAT.

EMERGE's lack of uptake was most probably linked to the meteorological data requirement of SWEAT discussed above. Development of a new submodel for SWEAT would benefit the application of EMERGE, because it uses SWEAT to predict soil temperature and moisture.

More generally, technical specification of models can be made more appropriate through the active involvement of a wider set of stakeholders in model development. If extension organizations are to use models to support farmer decision making, extension personnel will need to input data provided by farmers. Model data requirements should therefore be specified in terms which are meaningful to farmers. Scientists and farmers often have very different sets of criteria for classifying phenomena (cultivars, soils, weather, nutrients). The closer the input requirements match farmers' knowledge and classification systems, the more useful will be the model.

One of the factors associated with unsuccessful research projects in the tropics reviewed by Edwards & Farrington (1993) was inadequate attention to dissemination channels. They also felt that researchers themselves must take more responsibility for effective promotion and uptake of their models and associated output. This comment also applies to the projects studied in this paper. Little consideration was given to dissemination pathways at the start of these projects. In most cases the production of a model on a diskette was assumed to be the final project output. The funding period of these models was too short to ensure effective dissemination of the results. The dissemination pathways recommended by Garforth (1998) include: publications, leaflets, mass media, workshops and training and research collaboration. A lot of enthusiasm was created in scientific meetings where most of these four models were distributed. However, a database of individuals that received the models was not created and therefore there was little follow-up and feedback.

How can model uptake and development impact be improved?

Crop simulation modelling has been recognized as a tool which can help both farmers and scientists evaluate better the variability and risks of alternative technologies especially in semi-arid environments by national and international organizations such as DFID and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) (such as the use of PARCH in Kenya; Stephens & Hess, in press). The following ten points need to be considered for improving uptake and developmental impact of crop simulation modelling projects. Although our recommendations are based on only four DFID-funded resarch projects, they can be used as guidelines for managerial research-funding committees and individuals proposing to undertake modelling work in the semi-arid tropics.

Objectives. The objectives of the modelling project should be clearly specified, and information and justification on the need for the model to be developed should be given. The team should also specify the intended users and identify the ways in which they might use the model. The logical and practical links from model use to farmer decision making and the enhancement of household livelihoods should also be described. Garforth & Usher (1997) commented that the main factor influencing uptake by users is the relevance to them of the research output itself. It follows that potential users need to be involved in the project preparation phase.

Dissemination. Dissemination pathways should be planned well in advance during the project preparation phase. This requires an involvement of research and extension experts or social scientists from the project initiation phase up to the point where the output has been successfully disseminated. The lack of such personnel could have contributed to the general low uptake of these models. Although a socio-economist was present in some of the meetings of the PARCH suite modellers, dissemination was hardly discussed (Ellis-Jones, unpublished). In projects where funding was planned for dissemination, it was used for research instead due to lack of time to develop the models.

Collaboration with an institution and, if possible, farmers in the target country. A link with a local institution, which preferably includes a representative of that institution as a member of the model development team, is required. No such link or member existed in developing PARCH. On the other hand, developers of PARCHED-THIRST have a strong link with local institutions and their members participate in the development of the model. This should certainly contribute to the uptake of the follow-up model which is currently near completion. Passioura (1996) stated that 'the most promising use of simulation models as teaching aids is in educating farmers'. He explained that they are good observers and their involvement with models would make them even better observers.

Collaboration among modellers. A modellers' group should be formed and a newsletter prepared on a regular basis (e.g. biannually) during the project development phase. None of the developers in the PARCH suite of models produced periodical newsletters. A good example of this kind of practice is the agroforestry modelling project (FRP 1998). The group produces an Agroforestry Modelling Newsletter periodically and gives regular updates on achievements to members of the group.

Users' database. Potential users in national research institutions, universities and non-governmental organizations need to be identified and a database of people that are likely to benefit from the model created. None of the model developers had a complete list of either potential users or active users. Such practice, apart from losing contact with the potential users, makes it difficult to assess impact.

Workshop and training. As far as possible, evaluation of the model and its adaptation to the local environment should be done by organizing a workshop that includes the above mentioned users and key individuals as part of the dissemination process. PARCH was a good example of dissemination in this way and a lot of enthusiasm was created (Hess & Stephens 1994). Confidence in using the models can be improved by organizing regular training programmes.

Technical assistance. A delegated member of the model developers (preferably one who works for a local institution) should act as a contact person in case any of the users need further assistance. This was not done in the case of the PARCH suite. This is because after the project is finished the developers usually move on to different projects and are detached from the project (mostly due to lack of funding).

Follow-up. The delegated member should follow-up progress of the model among users by perhaps continuing the production of newsletter on a regular basis. After the initial evaluation (Stephens & Hess 1996), no follow-up was made for PARCH. The effect of this is reflected in the poor number of responses obtained from users in the target region (Fig. 1).

Evaluation. Evaluation of uptake and impact of the models should be carried out periodically. Models can become obsolete in a relatively short period of time if they do not keep up with the advancement of technology. Therefore, some provision and recommendations should be made to improve the models periodically.

Risk assessment. Farmers in the semi-arid tropics are not usually driven by mean increase in yield but by food security. In other words, they need to be able to know the risks involved. The model should be able to tell them what the risk factor is of crop failure if they followed a particular management strategy. As they stand, most of the models discussed do not offer a risk assessment facility. However, this might be possible by running the models several times with different parameters, but that would be beyond the scope of most extension agents.

One of the major sources of low uptake was lack of funding for dissemination. From the 10 guidelines outlined above, five (dissemination, organizing workshop and training, technical assistance, follow-up and evaluation) require longer time commitment from the funding body. Baker (1996) questions whether scientists are under pressure to conform to funding agency policy when writing proposals to compete for 'ever-tightening budgets'. If funding is less likely to be granted to projects of over three years duration, then there is rarely enough time to develop the models and effectively disseminate to potential users. Under these circumstances, it is not surprising that dissemination becomes the first casualty of relatively short duration projects. It raises an important question on the current methods of funding modelling projects with a life span of 2–5 years. Funding agencies need to realize the need for setting up funds for the dissemination process at least 5–10 years after the expected completion of a modelling project.

Research scientists in national and international institutions in the semi-arid tropics can use crop production models to evaluate and improve the poverty alleviation impact of their work. However, modelling should only be regarded as a means and not as an end-product. To quote from Danfaer (1991), 'Good models can be used to improve the design and interpretation of new experiments. Better experiments and better interpretation will increase knowledge. And increased knowledge is a basis for better models. Hence, experimentation and modelling in agriculture can support each other by a self-increasing process. This could lead to more efficient utilisation of research funds and eventually to improvements in agricultural production'.

The first challenge is to transfer the knowledge to researchers in the semi-arid tropics. This is facilitated technically by improving the user friendliness of the model and by limiting the number of parameters required to run the model without compromising its effectiveness. Involvement of users in the production and evaluation of the model would enormously help its uptake in the region. Where models are intended for use in advising farmers or improving their information base for decision making, the second challenge is to provide a mediating function between the model and the end user. In semi-arid contexts in developing countries, this will usually be through the public sector extension service and the wide range of non-governmental, farmer association and commercial organizations active in providing agricultural support services. The staff of such organizations will need exposure to the potential of models. Specific training and dissemination activities will be needed, including workshops, technical support, use of models within university and college courses, so that extension agents can collect and input model data, and then interpret the output and understand the risks involved in following certain management practices.

Despite the appropriateness of crop simulation models in the semi-arid tropics, their uptake, to say the least, has been disappointing. Modellers proposing to develop a model, need to extend the intellectual challenges posed by technical development of the model to transferability and uptake of the model by at least the intermediate user. Unless modellers improve the uptake of their models by users, and demonstrate their relevance in helping development, future funding for modelling is at risk.

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REFERENCES

Baker, J. M. (1996). Use and abuse of crop simulation models – Forward. *Agronomy Journal* **88**, 689.

Boote, K. J., Jones, J. W. & Pickering, N. B. (1996). Potential uses and limitations of crop models. *Agronomy Journal* **88**, 704–716.

Crout, N. M. J. & Azam-Ali, S. A. (1990). *A Review of Crop/Environment Models Appropriate to the LWMP, Botswana*. Nottingham: University of Nottingham, Physiology and Environmental Science.

Crout, N. M. J, Young, S. D & Bradley, R. G. (1997). *PARCH – Technical Manual*. Nottingham: University of Nottingham, Physiology and Environmental Science.

Daamen, C. C. (1997). Two source model of surface fluxes for millet fields in Niger. *Agricultural and Forest Meteorology* **83**, 205–230.

Daamen, C. C. & Simmonds, L. P. (1994). *Soil Water, Energy and Transpiration – A Numerical Model of Water and Energy Fluxes in Soil Profiles and Sparse Canopies. Project Report to NRIL*. Chatham: Natural Resources International Ltd.

Daamen, C. C. & Simmonds, L. P. (1996). Measurement of evaporation from bare soil and its estimation using surface resistance. *Water Resources Research* **32**, 1393–1402.

Daamen, C. C., Simmonds, L. P. & Sivakumar, M. V. K. (1995). The impact of sparse millet crops on evaporation from soil in semi-arid Niger. *Agricultural Water Management* **27**, 225–242.

Danfaer, A. (1991). Mathematical modelling of metabolic regulation and growth. *Livestock Production Science* **27**, 1–18.

Edwards, D. T. & Farrington, J. (1993). *Review of the Factors Influencing the Uptake and Impact of a Sample of Twenty-One UK-Supported Renewable Natural Resource

Research Projects. *ODI Network Paper 43*. London: Overseas Development Institute.

FRP AGROFORESTRY MODELLING PROJECT (1998). *Agroforestry Modelling Newsletter*. *No. 6, January 1998* . From internet web site – http://www.nmw.ac.uk/ITE/EDIN/Agro.

GARFORTH, C. (1998). *Dissemination Pathways for RNR Research: Socio-Economic Methodologies and Best Practice Guidelines*. Chatham: Natural Resources Institute.

GARFORTH, C. & USHER, R. (1997). Promotion and uptake pathways for research output: a review of analytical frameworks and communication channels. *Agricultural Systems* **55**, 301–322.

HATIBU, N., MAHOO, H. F., KAYOMBO, B. & MZIRAI, O. (1997). *Evaluation and Promotion of Rainwater Harvesting in Semi-Arid Areas of Tanzania*. Sokoine University of Agriculture, Soil-Water Management Research Group. Final technical report to NRI.

HESS, T., STEPHENS, W., CROUT, N. M. J., YOUNG, S. D. & BRADLEY, R. G. (1997). *PARCH – User Guide*. Nottingham: University of Nottingham, Physiology and Environmental Science.

HESS, T. M. & STEPHENS, W. (Eds) (1994). *An Evaluation of the PARCH Model for Simulating Maize Yield in the Arid and Semi-Arid Lands of Kenya*. Silsoe: Cranfield University.

MONTEITH, J. L. (1996). The quest for balance in crop modelling. *Agronomy Journal* **88**, 695–697.

MONTEITH, J. L., HUDA, A. K. S. & MIDYA, D. (1989). RESCAP: a resource capture model for sorghum and millet. In *Modelling the Growth and Development of Sorghum and Pearl Millet*. *Research Bulletin 12* (Eds S. M. Virmani, H. L. S. Tandon & G. Alagarswamy), pp. 30–34. Patancheru, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

MULLINS, C. E., TOWNEND, J., MTAKWA, P. W., PAYNE, C. A., COWAN, G., SIMMONDS, L. P., DAAMEN, C. C., DUNBABIN, T. & NAYLOR, R. E. L. (1996). *EMERGE – Users Guide*. *A Model to Predict Crop Emergence in the Semi-Arid Tropics*. Aberdeen: University of Aberdeen, Department of Plant and Soil Science, UK.

PARKER, C. (1999). Decision support systems: Lessons from past failures. *Farm Management* **10**, 273–289.

PASSIOURA, J. B. (1996). Simulation models: science, snake oil, education, or engineering?. *Agronomy Journal* **88**, 690–694.

STEPHENS, W. & HESS, T. M. (1996). *Report on the PARCH Evaluation Visit to Kenya, Malawi, Zimbabwe and Botswana*. Silsoe: Cranfield University.

STEPHENS, W. & HESS, T. M. (in press). Modelling the benefits of soil water conservation using the PARCH model – a case study from a semi-arid region of Kenya. *Journal of Arid Environments*.

STEPHENS, W., HESS, T., CROUT, N. M. J., YOUNG, S. D. & BRADLEY, R. G. (1997). *PARCH – Tutorial*. Nottingham: University of Nottingham, Physiology and Environmental Science.

WARHAM, E. (Ed.) (1998). *DFID and the Consultative Group on International Agricultural Research (CGIAR): The Competitive Research Facility 1990–1997*. London: Department for International Development.

YOUNG, M. D. B. & GOWING, J. W. (1996). *The PARCHED-THIRST Model – User Guide Version 1.0*. Newcastle: University of Newcastle, Department of Agricultural and Environmental Science.