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Participatory research in dryland cropping systems — monitoring and simulation of soil water and nitrogen in farmers' paddocks in Central Queensland

M. A. Foale[A,E], *M. E. Probert*[A], *P. S. Carberry*[B], *D. Lack*[C], *S. Yeates*[B], *D. Brimblecombe*[D], *R. Shaw*[D] *and M. Crocker*[D]

[A]APSRU, CSIRO Sustainable Ecosystems, 306 Carmody Road, St Lucia, Qld 4067, Australia.
[B]APSRU, CSIRO Sustainable Ecosystems, PO Box 102, Toowoomba, Qld 4350, Australia.
[C]Department of Primary Industries, Redlands Research Station, Cleveland, Qld 4163, Australia.
[D]Collaborating farmers from Capella and Banana, Central Queensland.
[E]Author for correspondence; e-mail: mike.foale@csiro.au

Abstract. Collaboration of researchers and service providers with farmers in addressing crop and soil management, using on-farm experiments and cropping system simulation, was negotiated in 2 districts in Central Queensland, Australia. The 2 most influential variables affecting crop productivity in this region (soil water and mineral nitrogen contents) and the growth of sown crops, were monitored and simulated for 3 years beginning in December 1992. Periodic soil sampling of large experimental strips on 3 farms, from paddocks that differed in cropping history and soil properties, provided robust datasets of change, over time, of soil water and mineral nitrogen status. Farmers participated in twice-yearly discussions with researchers, informed by the accumulating data, which influenced thinking about soil behaviour and possible new management strategies. As the study period coincided with a prolonged drought, so that cropping opportunities were few, the objectives of the work were modified to concentrate almost exclusively on the soil variables.

The contribution of the Agricultural Production Systems Simulator, which was used to simulate the measured changes in soil water and mineral nitrogen, was found by all participants to be useful. The APSIM output generally demonstrated close correspondence with field observations, which raised confidence in its applicability to local cropping systems. Exploration of hypothetical situations of interest to farmer participants, in the form of what-if scenarios, provided insights into the behaviour of the production system for a range of soil and seasonal conditions. The informed speculation of the simulator became a substitute for the farmers' own, more tentative, efforts.

The regular participative review sessions proved to be highly effective in stimulating the learning of both farmers and researchers. The farmers were able to feel comfortable as owners of the collaborative experiments and custodians of the learning environment. Clear evidence for the ongoing learning of these farmers appeared in post-collaboration practices and experiences.

Introduction

The grain cropping systems of north-eastern Australia are driven primarily by a climate characterised by unreliable rainfall (Hammer *et al*. 2000) and by soils, which for many years of cropping did not respond to fertiliser, but now, with declining fertility (Dalal and Mayer 1986), have begun to respond strongly. Managing crops under conditions of highly variable supplies of soil water and nitrogen (N) is of particular concern to dryland farmers in Central Queensland (Cox and Chudleigh 2001).

Farmers in Central Queensland have the opportunity to produce a range of crops in both the summer and winter seasons. Their decisions concerning which crop and when to sow are largely determined by a coincidence of adequate sowing rain with an appropriate minimum amount of stored soil water. Consequently, fallowing between crops is a common management strategy, enabling the build-up of soil water and to offset the risk of low in-season rainfall (Foale *et al*. 1997). However, the opportunity cost of a long fallow period includes low cropping frequency and, in some circumstances, an increase in soil erosion and solute leaching (Freebairn *et al*. 1991).

To facilitate sowing decisions, farmers have traditionally assessed soil water status as the depth of wet soil measured by a push probe or penetrometer (Fawcett *et al*. 1976). As this measure responds to the force that is applied, it can be unreliable in estimating soil water at depth, and is of no assistance in monitoring accumulation of mineral N. Hence farmers were slow to apply fertiliser in the absence of information about N status. Once it was clear that nutrient supply was limiting in some seasons, sampling of the soil surface (100–150 mm layer only) was recommended, as it

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had been reasoned that soil N declines with depth (Holford and Doyle 1992).

In 1992, a number of farmers and their consultants agreed to join researchers in exploring the potential and present capability of their soil resources. Ways were being sought to improve the efficiency of water and N utilisation through change in management built upon a series of collaborative on-farm research trials, which extended over 3 years (Cox *et al*. 1993; Foale *et al*. 1996). This paper reports on the outcomes of this research, both in terms of what was learnt about soil water and N dynamics and their management in such systems.

In the present study the themes posed by the participating farmers to their research collaborators were: Does my present practice achieve best management of my rainfall, soil water and N resources? Are there tools available that better measure and evaluate soil resources (to depth) to inform my management decisions?

The approach adopted in this collaborative on-farm research activity was one of Participatory Action Research (PAR) — a research approach that facilitates the 'production of knowledge that guides practice, with the modification of a given reality occurring as part of the research process' (Oquist 1978; McCown 2001). This approach acknowledges that science cannot elucidate the management of agricultural systems without real participation of the managers of such systems (Carberry 2001). Such a research paradigm has underpinned the Farmers', Advisers', Researchers' Monitoring, Simulation, Communication And Performance Evaluation (FARMSCAPE) portfolio of research activities (McCown *et al*. 1998; Hochman *et al*. 2000; Carberry *et al*. 2002), of which this particular case study represented a pioneering attempt at implementation.

One of the key research questions addressed in FARMSCAPE has been whether the scientific knowledge applied to real world management scenarios within computer simulation models can assist practitioners in better managing their farming systems (McCown *et al*. 1998). Farmers in northern Australia had largely not adopted computerised decision support systems (DSSs) (Hamilton *et al*. 1991; Ridge and Cox 2000; Hayman and Easdown 2002; Hearn and Bange 2002), although a number had been developed specifically for this region, their authors aspiring to provide agronomic recommendations. Those early DSSs were largely based on generalised inputs of resource and management information (e.g. Woodruff 1992). Through farmer group engagement, on-farm trials, soil characterisation, monitoring of crops, soils and climate, and participative application of the Agricultural Production Systems Simulator (APSIM) (McCown *et al*. 1996; Keating *et al*. 2002), the FARMSCAPE approach represented an alternative research programme to the DSS, addressing decision support intervention (Carberry *et al*. 2002; McCown 2002).

The objectives of this paper are to report results from the on-farm monitoring of water and N; to demonstrate the utility of the APSIM model in reproducing and adding value to measured results; to assist participants' understanding of the behaviour of their soil resource and provide ideas to manage it better; and to report on what was learnt by each group of participants from this PAR case study.

Materials and methods

Negotiation with farmer groups

In 1992, the researchers approached 2 existing farmer groups and their local public extension officers in Central Queensland seeking collaboration. Ten farmers agreed to become involved, 6 near Capella (23.08°S, 148.02°E, altitude 222 m) west of Rockhampton and 4 near Banana (24.48°S, 150.13°E, altitude 263 m) in the Dawson Valley, west of Biloela, Queensland. The non-farmer component of the collaborating team comprised 1 private consultant, 3 extension officers and 4 researchers. All the farmers were initially interested in the possible need for additional soil N on their winter (wheat) and summer (sorghum, sunflower) crops. Some were trialling N fertiliser application, while others were testing pulse crops, such as mungbean, chickpea and lablab, as a means of reducing the need for N fertiliser.

Six of the farmers volunteered at least 1 paddock with the intention that they would carry out experiments of interest for the broader farmer group and the researchers. Proposed experiments included the application of N and phosphorus fertilisers and the use of a lablab leguminous cover crop to restore soil N following an intensive cereal cropping sequence. There was no pre-arranged plan of action, in contrast to a conventional experimental project undertaken on a research station where even the sowing date might be fixed by resorting to opportunistic irrigation. The precise details of any trial would emerge as soil states were monitored and planting opportunities emerged.

Conducting the on-farm trials — general

Anticipating that crops might soon be sown, sampling by the researchers was done (there was no local service provider to do such work for the farmer at this stage) in nominated paddocks in December 1992, to establish the initial state of soil water and mineral N. There was a strong similarity in the general physical properties of the soil being cropped on these farms. In a survey performed by the Queensland Department of Natural Resources (B. Forster unpublished data) all the sites chosen fitted the following description: 'a moderately-deep black cracking clay with a very dark brown, self-mulching, medium clay surface over a strongly-structured medium clay sub-soil.' The soil depth above a weathering zone of mudstone or basalt varied from 60 to 90 cm.

Different treatments were accommodated in these experiments, which comprised long (300–400 m), narrow (12–16 m) strips that the farmer could fertilise, sow and harvest separately.

As the project proceeded under the constraint of persistent drought conditions, the limited planting opportunities that arose resulted in very low yields from any sown crops. It became necessary, because of lack of opportunity, to concentrate the intense work on the Crocker, Shaw and Brimblecombe sites. As explained later in detail, the Crocker farm site reverted to a single treatment for the purposes of this paper, the Shaw farm had several rates of N fertiliser, and on the Brimblecombe farm the principal comparison was between previously cropped land and land newly cleared and fallowed for the first time.

Soil water and mineral N status were measured at 4 representative locations spaced equally along each experimental strip. Two soil cores of 44 mm diameter, reaching to the full depth of the potential root-zone of a crop, were taken from each representative location. The cores were divided into depth intervals of 0–15 cm, 15–30 cm and each 30 cm thereafter to a depth of 90 cm, in most paddocks. Within each representative location, the 2 samples from each layer were bulked together for measurement of gravimetric water content (dried at 105°C), and of nitrate-N concentration, using extraction with 1 mol/L KCl (Best 1976). The samples were also used to determine the concentration of organic carbon by the Walkley-Black method adapted for spectrophotometric determination (Sims and Haby 1971).

The quantity of plant-available water that could be stored in the profile [Plant Available Water Capacity (PAWC)] was also determined for 1 representative soil sample from each of the 2 regions, employing a variation of the soil characterisation procedure of pond irrigation and growth of a rain-sheltered crop described by Dalgliesh and Foale (1998). Daily rainfall and temperature were measured using an automatic weather station at the Shaw and Crocker farms, while only daily rainfall was measured at the Brimblecombe farm, which was located about 20 km from Shaw farm.

Periodic gatherings of the farmers in each region were convened in order to present new data and observations, and, when appropriate, to perform simulations that served to broaden the scope of discussion. The protocol for these meetings, held in a small local hall or a farmer's home, was designed to maximise the input of experience, ideas and interpretation of all participants. The APSIM output was given the status of another 'opinion' within the group.

Conducting the on-farm trials — specific details

Crocker farm. Six treatments were imposed, being combinations of phosphorus (P) and sulfur fertiliser, but these showed no effect on the observed soil water and nitrate-N data. Thus, the mean across all strips is used as the observed data to compare with the output from the model. The soil was first sampled on 9 December 1992 for determination of soil water and nitrate-N and these data were used to initialise simulation on APSIM. Mungbean was sown in January 1993 and sorghum in September 1993.

Shaw farm. The treatments imposed were combinations of fertiliser N applied as urea — rates of 0 and 28 kg/ha of N were applied in May 1992 (a few months before the experiment began), while 0, 55 and 83 kg/ha were superimposed in December 1992, generating aggregate N doses of 0, 28, 55, 83 and 111 kg/ha. The soil was initially sampled on 6 December 1992 to determine soil water and nitrate-N, and these data were used to initialise APSIM

Any effect of the early application would be accommodated by the measured values that were used to initialise the model at the soil state of December 1992. For simulation of the trial, 2 N inputs have been used, 0 and 69 (the mean of 55 and 83) kg/ha, applied in December 1992. A wheat crop was sown in May 1994.

Brimblecombe farm. Treatments imposed included a factorial combination of 0 or 28 kg/ha of N as urea and 0 or 45 kg/ha of mono-ammonium-phosphate (MAP) (6 N, 10 P) applied on 26 December 1992 to land that had been cropped with chickpea or wheat in the previous winter or land that had been recently cleared. Soil sampling was done on 7 December 1992 to determine soil water content and nitrate-N, with these data used to initialise APSIM. A wheat crop was sown in May 1995. Simulation of the trial was simplified to a study of the impact of previous land use (new land *v.* cropped land) with a common application of 17 kg/ha of N (i.e. the mean of the 4 rates applied).

Simulation of the on-farm trials

The model used to simulate the experiments was APSIM version 1.61 (McCown *et al*. 1996). The APSIM modules SoilWat2 and SoilN2, which represent the soil water balance and the dynamics of soil organic matter, including N mineralisation, have been described by Probert *et al*. (1998). The crops were modelled using the APSIM modules for sorghum (APSIM-SORG), wheat (APSIM-NWheat) and mungbean (APSIM-Mungbean); simulation of the summer weeds that grew in the trial on Crocker farm was done using the sorghum module with the rooting depth restricted to 60 cm.

Model parameterisation issues

The water holding characteristics of the soil on each property were derived from the observed data. For each soil layer, the measured data provided estimates of the drained upper limit (based on the wettest observed moisture content) and the lower limit (driest observed). On Crocker farm, soil sampling was also done in March 2000 to gain an improved estimate of the drained upper limit (DUL) in the deeper layers; on this occasion wetting up had penetrated to the 60–90 cm layer. Further, the assumption that these clay soils obey normal shrink–swell behaviour was used to calculate the bulk density of the wet soil, from which can be derived total porosity and saturated water content (Dalgliesh and Foale 1998). The soil profiles that were wetted up were located close to the trial sites; they were similar soil types to the respective neighbouring paddocks (B. Forster pers. comm.), and thus provided a check to compare with the other estimates.

On Brimblecombe farm, it was assumed that the same soil water properties were applicable for both the new and the cropped land.

The model was initialised with the measured soil organic carbon (using a factor of 1.3 to correct the Walkley-Black values for incomplete recovery). The other factors affecting N mineralisation are the carbon (C) : N ratio and the proportion of the soil organic matter that is inert — that is, not susceptible to decomposition (Probert *et al*. 1998). For these datasets, it was found that the observed data were consistent with the hypothesis that little mineralisation occurs in the deeper layers. In each case, the fraction of inert C was at 0.75 in the 30–60 cm layer and 0.9 below 60 cm.

Communication events

The on-farm collaborative approach has itself generated a particular set of experimental data in the form of observations on the outcome of the interactions that were experienced. It was agreed at the outset that each farmer would take responsibility for the management of the experimental strips, including any weed control, and particularly the sowing and harvesting of crops. The researchers agreed to operate the weather station, characterise the soil with respect to PAWC and monitor the state of the production system using soil coring and crop sampling when appropriate.

The collaborative quality of the project was sustained by means of the more-or-less regular (twice-yearly) discussions between the partners, namely farmers (including those neighbours who had lower-intensity or nil actual field work on their properties), the advisers and the researchers. On each occasion, recent field activities were reported and new data presented, simulations were done where appropriate and this was followed by discussion. In spite of the fact that very few successful crops were grown, due to the lack of timely rainfall in most seasons, all the participating farmers remained active in the discussion groups throughout.

Results

Collaboration between partners

There were always close interactions between the resident farmer and the researchers during field visits for sampling, observations and simulation sessions. As data from soil, plant growth and weather recording became available, the performance of the soil resource and the production system (when applicable) was interpreted in the light of the long-term and recent experience of the farmer and his neighbours, who were informed by their local knowledge. The researchers contributed the new data and, from time to time, used the value-adding capability of the APSIM model to increase understanding of the response of the soil to particular rainfall events and extended dry periods. The postponement of cropping, due to dry weather, led to the farmers and advisers juggling, and frequently updating, potential options for opportunity cropping.

The computer-aided discussions followed a what-if format in which variables, over which the farmer has control, such as choice of cultivar, sowing date, fertiliser application, plant density and row spacing, were tested. A period of 30 years of past rainfall and other climate records was usually explored in these sessions, generating a set of simulated yields. The farmers affirmed that this was highly thought-provoking, even though the absence of sown crops deprived the team of current-season crop data. As there was no opportunity for evaluation of the simulator's outputs against crop performance, attention was focused on soil variables.

Despite this limitation, an evaluation of farmers' response to the research, performed late in 1995 (J. Coutts pers. comm.), drew the following conclusion: 'the project resulted in knowledge gain and practice change by most producer participants; producers maintained their confidence that collaborative on-farm trials would yield significant dividends; computer models were viewed as having potential to assist with decision making, particularly if linked to local on-farm results'.

The weather

The 3-year life of the project coincided with a prolonged severe drought, punctuated by a few intense and poorly timed rainfall events. This is shown by the rainfall record for each of the 3 farms, 1993–95, presented in the upper graph of Figures 1–3. The figures also show the sowing date for the few crops actually sown and reveal that in each case there was no significant follow-up rainfall. Crop establishment was very poor, subsequent growth was limited and harvesting was mostly considered not to be worthwhile.

Soil water data

The lack of significant cropping meant that data generation was almost exclusively for soil water (Figs 1*a*, 2*a*, and 3*a*) and nitrate N (Figs 1*b*, 2*b* and 3*b*). The figures also show both the observed and simulated data. While the long dry periods diminished soil water markedly, both water and N accumulated episodically in response to the few significant rainfall events that took place. We comment first on the observed data.

The upper 3 layers of the Crocker and Shaw farms show fairly similar values for maximum water content, suggesting similarity in physical properties, whereas Brimblecombe farm shows somewhat higher values. The fourth layer at the Crocker and Shaw farms (Figs 1*a* and 2*a*, respectively) in both cases had low maximum water content, which related to the presence of coarse-textured parent material at that depth. The soil on Brimblecombe farm, in contrast (Fig. 3*a*), held more water in this layer in the uncropped strips.

On Shaw farm the range of observed fluctuation in total profile water was 100 mm, and at Crocker farm the range was 90 mm. At both these sites, which experienced heavier rainfall than Brimblecombe farm in early 1994, there was a somewhat greater change in deep soil water than at Brimblecombe farm — especially in the 30–60 cm layer.

On Brimblecombe farm, at the outset (Fig. 3*a*), the profile on the newly-cleared land was drier, by about 60 mm — particularly at depth — than the cropped land. The results for the whole profile show that, in spite of significant rainfall events in late 1993 and early 1994, this difference had been reduced by only 10 mm by the end of the observation period. The data for the 4 soil layers show that the difference resided at depth (layers 30–60 and 60–90 cm). The small increase in water content of these layers was about the same in both soils, thereby preserving much of the initial difference.

Mineral nitrogen data

On Crocker farm (Fig. 1*b*), 150 kg/ha of mineral N accumulated in the whole profile, on land with a 15-year cropping history. Unlike the Brimblecombe and Shaw farms, only about 50 kg/ha of the mineralised N moved to the deeper soil layers (below 30 cm). The weather at Crocker farm differed from the other farms because there was only 1 major wetting of the soil during the whole 3-year period. Nitrogen mineralised subsequent to that event remained in the surface layer because the rainfall between March 1994 and June 1995 was so light that only a small amount of water moved to layer 2 of the profile (Fig. 1*a*)

On Shaw farm, the variability in the initial soil nitrate-N data was such that no consistent effects were found due to the May 1992 application rates (data not shown), but effects from the second (December 1992) application were clear and consistent. The pattern of mineralisation and movement of mineral N within the profile (Fig. 2*b*) was somewhat similar on the Shaw unfertilised land to the cropped land on the Brimblecombe farm (Fig. 3*b*). The comparison at Shaw farm was between 69 (mean of 83 and 55) kg/ha of fertiliser N and nil fertiliser N. The observed N content of the whole profile showed early divergence, to the extent of 60 kg/ha between the treatments. Some N was removed by the 1994 wheat crop (perhaps as much as 47 kg/ha — see discussion of the simulation of this crop), and much of the remainder moved to layer 3 (30–60 cm), the amount being greater where fertiliser had been applied (Fig. 2*b*).

On Brimblecombe farm, any effects of the fertiliser treatments on nitrate-N measured in the soil at subsequent samplings was small compared with the much greater effects shown by the comparison between new land and cropped land. This is shown for whole-profile N (Fig. 3*b*) by a large divergence between the cropped and the newly-cleared sites. There was an accumulation of mineral N, over the period, of 135 and 280 kg/ha in old and new land respectively, showing that the new land generated mineral N at more than double the rate of the cropped land. In the first year, there appeared to be some movement of N between the upper and the second layer. Then there was a substantial transfer from both of these layers to layers 3 and 4, following the large rainfall event (194 mm over 9 days) early in 1994. The final observations show the development of a significant bulge of mineral N in layers 3 and 4, totalling 290 and 135 kg/ha on new and old land respectively. At this time the combined upper 2 layers, on the other hand, contained only 60 and 30 kg/ha of N on new and old land respectively, which differed little from their content at the beginning of the study.

Simulation results

Crocker farm (Fig. 1a and b). The simulated soil water output shows the water use by the mungbean crop that was sown in January 1993. The model simulated, with reasonable agreement, the growth, grain yield and N uptake of this crop. Total observed dry matter (DM) at maturity was 831 kg/ha and simulated was 957 kg/ha; observed grain yield was 338 kg/ha and simulated was 315 kg/ha; and observed N uptake was 18 kg/ha and simulated was 25 kg/ha.

The sorghum crop sown in early October 1993 did not grow well, due to lack of follow-up rainfall. It had a total biomass of only 482 kg/ha on 14 December 1993. In terms of the simulated soil water, there was little impact from this failed crop, and the observed data certainly showed that little water was used from the 15–30 cm layer or below. This suggests that the only water present in these layers, during the life of the sorghum crop, was unavailable to the crop, apparently being held at or below the lower limit of extraction for sorghum.

The soil water story during the monitoring period is dominated by the major rainfall event in March 1994, when

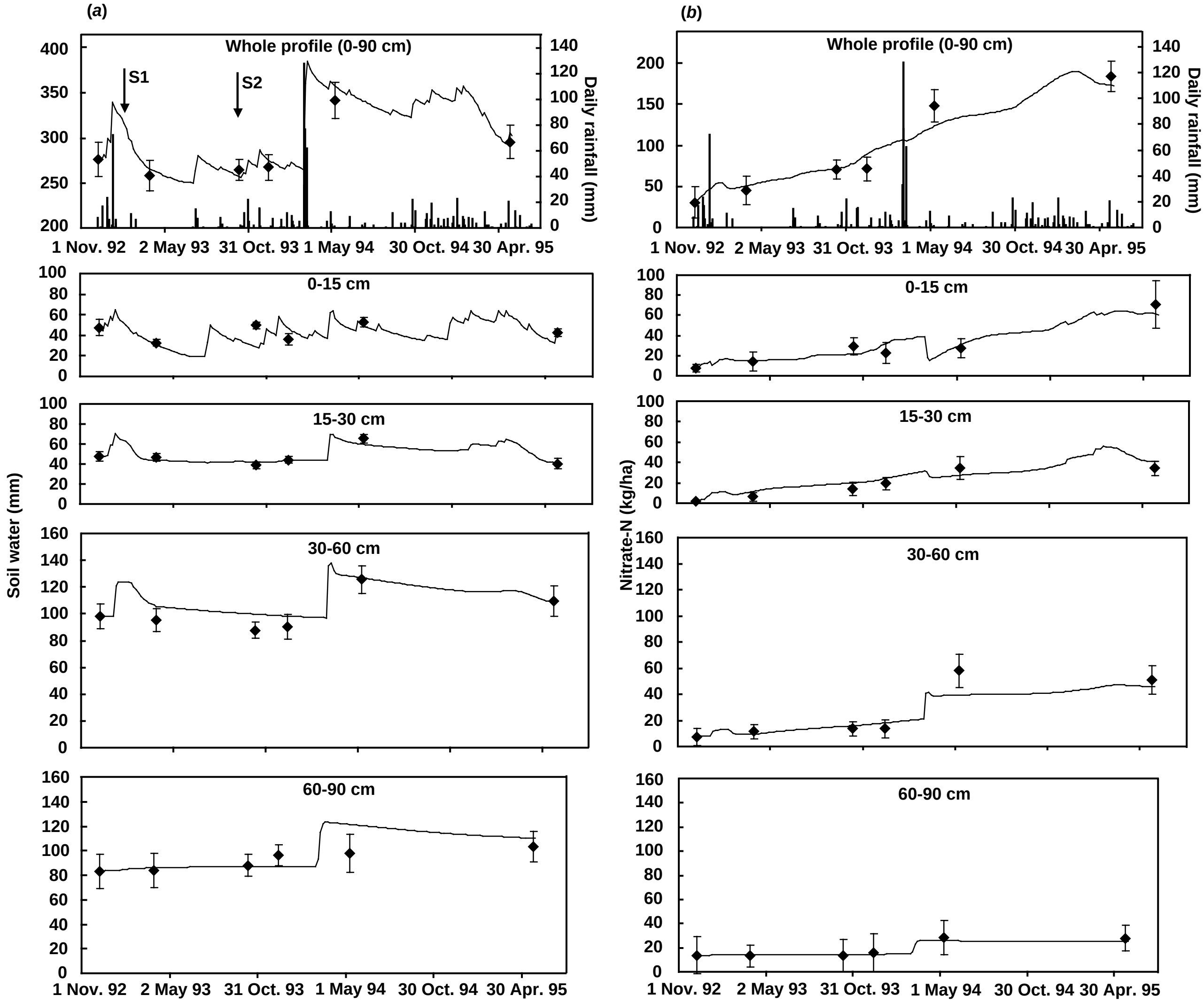

Figure 1. Crocker farm. (*a*) Upper section: daily rainfall (histogram) and whole-profile water content. Points represent measured data, error bars show ± s.d., and the plotted line shows the output of simulation. Lower section: water content of 4 layers of the profile. (*b*) Upper section: daily rainfall (histogram) and nitrate nitrogen (N) content of the whole profile. Points represent measured data, error bars show ± s.d., and the plotted line shows the output of simulation. Lower section: N content of 4 layers of the profile.

238 mm fell over 3 days. The observed data suggested that this caused little change in the soil water content of the 60–90 cm layer. To model this behaviour, a high proportion of the rainfall has to run off. Following the recharge of the profile in March 1994, there was some drying of the surface layer through the winter period. However, to simulate the more rapid drying that occurred in summer 1995, it was necessary to assume that there was some water use by weeds, which had been noted by the farmer to comprise a light infestation.

The observed data showed a rapid increase in mineral N following the wetting up of the soil in early March 1994, mostly in the 30–60 cm layer. Below 30 cm, there was little change in N content before that date, suggesting that either there was limited mineralisation potential at these depths or the soil was too dry for mineralisation to proceed. That there was no continuing increase in N after the soil had wetted up favours the limited potential option. It was difficult to parameterise APSIM to leach enough N into the deeper layers and to retain it there. Note that the N data showed an increase in the 60–90 cm layer, even though there is little evidence in the observed water data to suggest that the wetting front had reached that layer. However, the error bars on the water data for that sampling are large (Fig. 1*a*).

Simulation of the sorghum crop, sown in October 1993 and maturing in January 1994, provided an aboveground uptake value of only 14 kg/ha of N, compared with the measured uptake of 10 kg/ha at the anthesis harvest on 14 December 1993. After the sorghum crop, little nitrate-N was present in the surface layers that could be leached to deeper layers during the high rainfall event in March 1994.

Shaw farm (Fig. 2a and b). There was some movement of water into the 15–30 cm layer in September and December

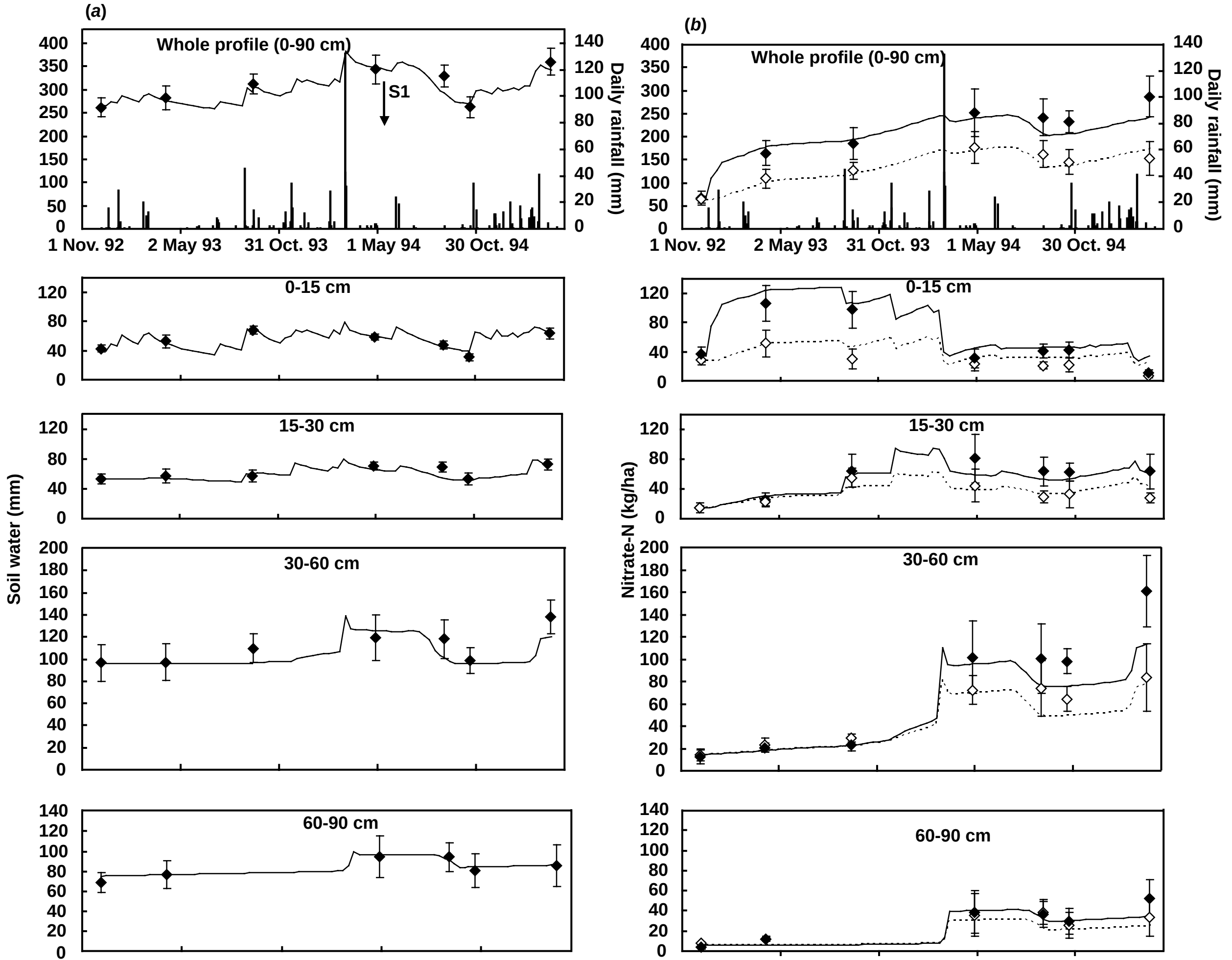

Figure 2. Shaw farm. (*a*) Upper section: daily rainfall (histogram) and whole-profile water content. Points represent measured data, error bars show ± s.d., and the plotted line shows the output of simulation. Lower section: water content of 4 layers of the profile. (*b*) Upper section: daily rainfall (histogram) and nitrate nitrogen (N) content of the whole profile. Points represent measured data, error bars show ± s.d., and the plotted lines show the outputs of simulation. Lower section: N content of 4 layers of the profile. The treatments compared were 0 (◇) and 69 (◆) kg/ha of N fertiliser.

1993, before the large rainfall event of February–March 1994 when water moved down to layers 3 and 4. The 1994 wheat crop did not grow well. It was patchy, and total biomass in September was estimated by sampling to be only 419 kg/ha. At maturity, sampled total biomass was 813 kg/ha, with grain DM of 237 kg/ha. The simulation predicted a much bigger crop. Even when average plant density in the simulation was reduced to 10 plants/m^2, the model output at maturity was 2170 kg/ha of total biomass and 47 kg/ha of plant N, with only very small effects due to the different N fertiliser treatments. Given the very low water supply, N was not likely to be limiting at this site, even on the nil fertiliser land. A very uneven crop stand was observed and this has not been fully captured by the simulation.

APSIM generally was satisfactory in simulating the soil water dynamics, except for generating too rapid uptake of water from the 15–30 and 30–60 cm layers by the 1994 wheat crop. The results, both measured and simulated, indicate that the N fertiliser applied in December 1992 remained in the soil profile and was fully accounted for as nitrate-N in the samples taken. In Figure 2*b*, the results have been combined across pairs of treatments (treatments with nil N applied in December 1992 *v.* those with N applied) to reduce sampling noise. For the whole profile (0–90 cm), the simulation of nitrate-N provides essentially parallel results throughout the whole trial, which agree closely with the observations. The tendency to over-estimate the uptake of N by the 1994 wheat crop is reflected in the simulated change in soil nitrate-N.

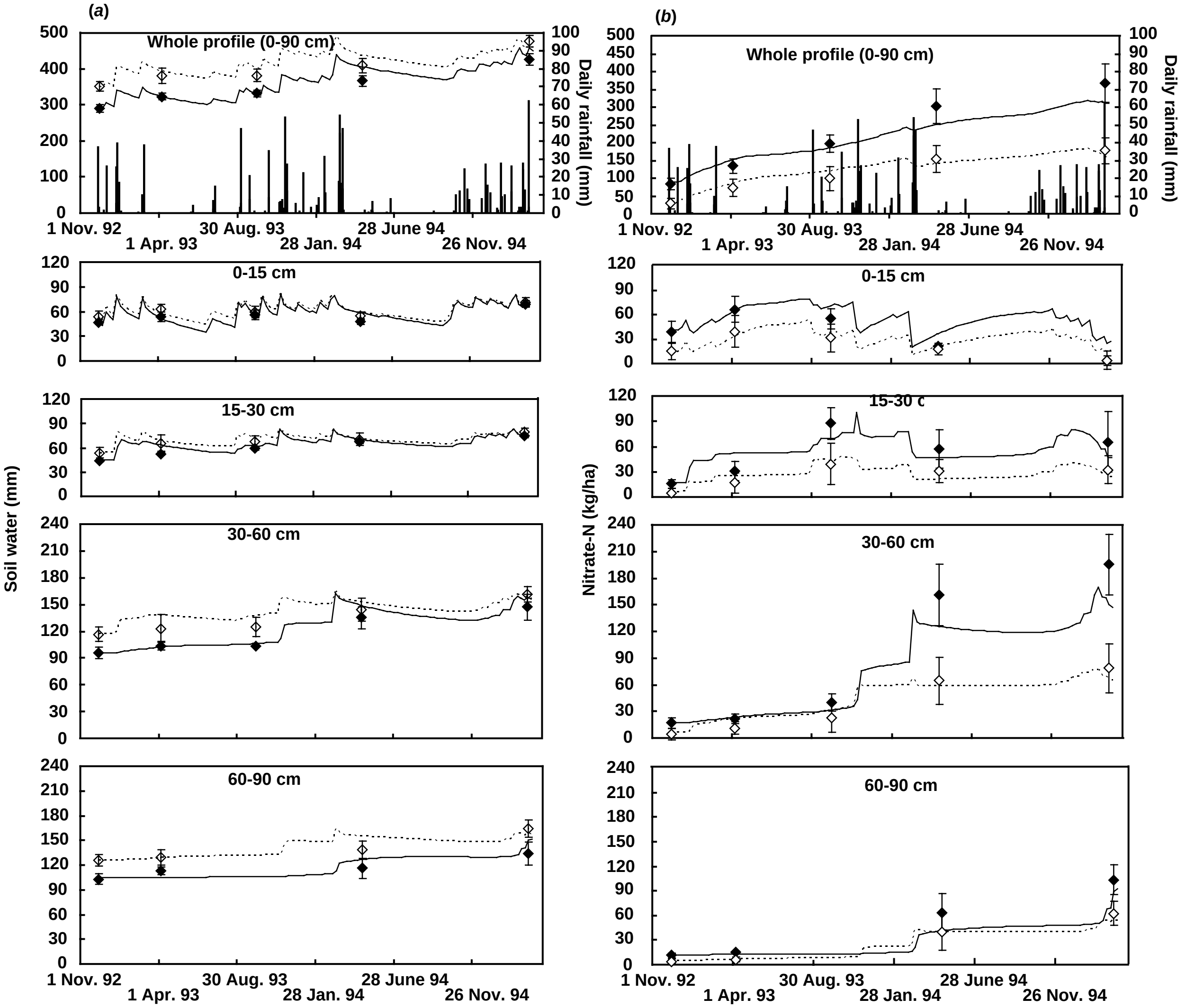

Figure 3. Brimblecombe farm. (*a*) Upper section: daily rainfall (histogram) and whole-profile water content. Points represent measured data, error bars show ± s.d., and the plotted line shows the output of simulation. Lower section: water content of 4 layers of the profile. The treatments compared were previously cropped land (◇), and new land (◆). (*b*) Upper section: daily rainfall (histogram) and nitrate nitrogen (N) content of the whole profile. Points represent measured data, error bars show ± s.d., and the plotted lines show the outputs of simulation. Lower section: N content of 4 layers of the profile. The treatments compared were previously cropped land (◇), and new land (◆).

The simulation values, plotted for the individual layers at Shaw farm show a progressive redistribution of N from the surface layer into the deeper soil layers, which matches closely the observed changes in water content. Until the large rainfall event of February–March 1994, there was little change in N content below 30 cm. But when the whole profile wet up (in response to 175 mm of rain over 2 days), the wetting front simulation showed movement beyond 90 cm, taking some N with it.

The poorest aspect of the model's performance is its failure to capture fully the increase in nitrate-N, shown in the observed data in early 1995 for the 30–60 and 60–90 cm layers. There are 2 issues related to this: first there has not been enough simulated mineralisation to provide the total amount of nitrate-N that was observed: and second, the amount and distribution of rainfall would not have been expected to be capable of moving the N into the deeper layers (the simulated change in water content of the 60–90 cm layer appears to be insufficient). Changing the soil's N mineralisation potential to try to capture the observed behaviour in early 1995 reduces the goodness of fit that was achieved earlier in the trial. Alternatively one might suggest the high nitrate-N in the 60–90 cm layer is an indication of mineralisation occurring *in situ*. There is, however, no evidence that this occurred through the preceding sampling periods when soil water content was similar.

Brimblecombe farm (Fig. 3a and 3b). Satisfactory agreement between the simulations and observed data was obtained with the assumption that the soil water properties were the same for both the new land and cropped land, with the soils differing only in their initial soil water content. In general the simulation of water content (Fig. 3*a*) matched the observed values reasonably well, tending to over-estimate water capture from large rainfall events such as late 1993 and early 1994.There is also close agreement between the water contents of the individual layers. The nitrate-N data also show a reasonable match between simulated and observed mineral N for the whole profile, and for the separate layers (Fig. 3*b*).

An observed increase of 30–35 mm water in the 60–90 cm layer was accompanied by an increase of 60 kg/ha of N on old land and 100 kg/ha of N on new land. The simulation matches these observations closely in that layer, but tends to underestimate mineral N accumulation in the 30–60 cm layer, especially on the new land. It is difficult to reconcile the significant increase in nitrate-N that occurred in the 60–90 cm layer with the small change in soil water content.

Discussion

In spite of an almost complete absence of harvestable crops during the 3 years of this collaborative project, a great deal was achieved. The farmers, their advisers and the participating researchers all engaged for the first time in joint planning and management of field experiments, and each learned from the experience. Learnings encompassed expanded knowledge of the farming systems in Central Queensland from which emerged modified paddock management practices. A key outcome from this work was learning how participatory research processes may operate. This pioneering experience provided the foundation for a subsequent 10-year programme of research, which has further developed and derived benefits from participatory research approaches (Carberry *et al.* 2002).

The soil water and mineral N data presented in this paper were closely matched, in general, by the simulation outputs, building confidence in the potential usefulness of APSIM in revealing the behaviour of the soil system. However, the discussion sessions became a mixed experience for the farmers as the drought persisted, leading to expressions of frustration at being able to 'grow crops only on the computer!'

The absence of significant cropping meant that there was a sustained focus on the behaviour of the soil variables, namely water and mineral N. For the farmers, the conversion and secure retention within the profile of fertiliser N was highly significant. They were relatively new to the use of fertiliser and had expected, based on information from elsewhere, that fertiliser N might be lost due to either waterlogging or leaching if there was no crop uptake of N in the short term. Rather, observations from on-farm trials reported in this paper demonstrated that both fertiliser N, and mineral N released from organic reserves, remained within the root-zone of the soil profile, moving slowly downwards, but not being leached, even by the very intense rainfall event that all 3 sites experienced in early 1994. The participating farmers concluded: 'It was a relief to learn that for N, even if there was no crop to use it, I didn't lose it.' 'I can see now that it's cheaper to buy N than to grow legumes.' 'This experience confirms that I can apply N early, and be able to concentrate on the planting job alone later on.' 'Now that I know about the build-up of N, I am not as hooked on planting date.' 'The lack of crops actually created an opportunity to learn a lot more about N in the soil.'

From these trials the researchers had the opportunity to learn how well APSIM performed in simulating results from large scale, on-farm experiments. As it turned out, the trials provided the opportunity to test APSIM simulations when dealing solely with soil water and N, and largely free from the concurrent simulation of a crop. Probert *et al.* (1998) had shown good agreement between APSIM outputs and crop and soil observations from researcher-managed experiments. Foale and Carberry (1996) provided a report on the good performance of APSIM in simulating the yield of commercial crops. This paper adds to the reported cumulative experience by having demonstrated that APSIM, appropriately parameterised, was able adequately to simulate soil water and N, as measured in farmers' paddocks over a 3-year period.

The dominant issue in terms of usefully simulating the behaviour of water at all 3 sites is to partition the large rainfall amount, which fell in March 1994, between runoff and infiltration, so that the soil wets up to a depth corresponding to what was measured. The water flux through the soil causes a redistribution of nitrate-N in the profile, which also needs to be calculated correctly. The model parameter that has a direct influence on runoff is the curve number (Probert *et al.* 1998). The depth to which the water penetrates also depends on the water holding capacity of the soils. For these situations, the measured data show that a high proportion of the rainfall received in early March 1994 must have run off, thus necessitating the use of high curve numbers. Over the 10-day period at the beginning of March 1994, the calculated runoff was 119 mm at Shaw farm (57% of rainfall), 160 mm at Crocker farm (52% of rainfall) and 94 mm at Brimblecombe farm (49% of rainfall).

In contrast to specifying the water characteristics, little difficulty was encountered in specifying the APSIM-SoilN2 module so that the rate of mineralisation was in broad agreement with the observed data.

There are some major implications of this work for the management of the paddock component of a cropping system. The farmers have concluded that core sampling of the profile to full crop rooting depth is essential in order to monitor the N resource, and to decide if fertiliser, beyond a starter dose, is actually needed. Soil coring also proved to be a significant aid to learning about available soil water, relating measurement on samples to observations done by the farmer with a push probe. Learning of the close relation, demonstrated by simulation, between yield and the quantity of available soil water, has given the farmers greater confidence to sow and anticipate a particular yield. For example; 'I use the rod probe to check soil water but can see now that the simulator makes better use of the information than I was making.' 'I am now looking at opportunity cropping and would not hesitate to double crop knowing that water and N are there.' 'My thinking has gone right away from worrying about varieties to concentrating on soil issues.' 'Involvement with the sampling has made me more observant and analytical, building confidence.' 'Greater knowledge makes me confident to anticipate a yield, and my banker responds to confident plans.' 'The simulator is especially good for tracking soil N — I never doubted that it would make sense.'

This work has enabled the research and extension participants to confidently formulate recommendations for paddocks of similar soil types. The behaviour of these typical soils, which had cropping histories ranging from 0 to 30 years duration, could provide clear guidance for many farmers in the region. Land with no previous cropping history clearly undergoes the release of N at a rate considerably greater than the rate of likely use of any crops in the short term (e.g. in excess of 100 kg/ha.year, Brimblecombe farm). The results suggested that released mineral N would continue to accumulate without serious leakage and without any adverse effect from the excess, except possible denitrification in the unlikely event of prolonged waterlogging. The paddock will support many years of cropping, free of limitation attributable to inadequate N supply. In contrast, after 12 years or so of cropping, the data from Crocker farm (Fig. 1*b*) showed N mineralisation at the rate of about 50 kg/ha.year, which would barely supply the needs of an annual grain crop yielding 2 t/ha. These were exceptionally dry years in which N release from the organic reserve would have been lower than in an average year, but the trend of reducing mineralisation on older land is clear. Regular checking of soil mineral N both for the total amount in the root-zone, and for its distribution in relation to the current depth of plant available water, would be a wise practice. Within a few years of the completion of this work, combined with other related efforts at addressing the soil N balance (Lawrence *et al.* 2000), deep soil sampling for N had become recommended practice in north-east Australia (Foale and Goode 1998), and the number of deep soil samples analysed for N content had increased exponentially (Carberry *et al.* 2002).

The farmers' influence upon the overall planning and later modification of the research, development and extension process was considerable. In contrast to the conduct of agronomic trials on an experimental farm run by researchers, where there would have been none or limited 'owned' results for 3 years due to the drought, the farmers waited eagerly for each update on the state of the soil resource under their enforced fallows. Having a desire to better understand the behaviour of the soil and to anticipate the state of the system 'when the drought broke', they were posing different questions compared with the researchers whose focus tended to drift back to the use of the simulator. The farmers were asking: 'Is my investment in fertiliser still secure?' 'How differently do I manage the new land alongside the old?' 'How often should we expect to experience a run of years like this?'

There was also this comment at the end: 'We felt a bit sick of growing crops on the computer because we were fed up to the eyeballs with the drought.'

The researchers background in station-based research was challenged by the failure of experiments to materialise due to the lack of sowing opportunities. Their dedication to prior research objectives was shaken by the challenge. The farmers, more familiar with weather-induced delays, sustained a helpful level of enthusiasm, especially once the state of the soil resources became a primary focus of attention. The researchers' objective then switched to simulation of the change in soil water and mineral N, and adequate parameterisation of the simulator to cope with the diverse environments under study.

Conclusions

As a result of this pioneering implementation of PAR in a dryland farming environment in Australia, it can be concluded that both farmers and researchers gained valuable knowledge. In terms of knowledge of the system, there were major revelations especially about the behaviour of mineral N in these shallow clay soils, relieving the farmers of the belief that fertiliser N might be lost when a crop could not be sown. The behaviour of mineral N also challenged the specifications of the simulator. Clearer guidelines have emerged from this work for the monitoring and management of mineral N. Finally, the whole process of unilateral formulation of research objectives by scientists was challenged as they had to respond to the attitude of the farmer 'owners' of the process in this case, in order to redirect attention from model testing to deeper understanding of soil matters.

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