Agricultural Systems 106 (2012) 33–45

Contents lists available at SciVerse ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Farmers use intuition to reinvent analytic decision support for managing seasonal climatic variability

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ARTICLE INFO

Article history:
Received 24 May 2011
Received in revised form 23 October 2011
Accepted 30 October 2011

Keywords:
Decision support
Simulation
Information system
Cognitive system
Intuition
Climatic risk

ABSTRACT

The FARMSCAPE Information System emerged in a long-running research program aimed at making simulation models useful to Australian farmers in managing climatic variability. This paper is about how well it has worked. This is reported in relation to two standards: (1) the value to thinking and action expressed by farmers and their consultants, (2) correspondence with theory about learning and judgement in uncertain external environments. The former utilises recorded narrative interviews with participants over many years. The latter uses a cognitive framework drawn from theory of judgment and decision making featuring the relationship between intuition and analysis (McCown, 2011).

The cognitive theory framework makes sense of several evaluation surprises. The first was high enthusiasm by largely-intuitive farmers for an analytic approach to soil water in conjunction with a newly-appreciated "bucket" metaphor for water balance. The second surprise was the virtual absence of soil water measurement 10 years later. This had been replaced by various intuitive estimates, calibrated to maintain a heuristic relationship with regard to the "bucket" as a resource.

Farmers and their advisers were facilitated in using simulation for thought experiments and planning under climatic uncertainty. Benchmarking enabled problem solving in documented conditions. Scenario analysis using historical climate records supported thought experiments by providing probability distributions that were valued for shaping expectations as a "history of the future". In retrospective evaluation interviews, researchers were surprised to find that yield forecasting and tactical decision making, anticipated to be analyses that were both site- and season-specific forecasts, had served farmers as "management gaming" simulations to aid formulating action rules for such conditions, thus reducing the need for an on-going decision-aiding service. Equipped with their soil monitoring techniques and with their heuristic rules, farmers still reserved a place for simulation "when you've got a planting situation out of the ordinary."

Theory without experiment is empty; experiment without theory is blind (Thagard, 2005, p. 8).

1. Introduction

This paper concerns a long running research program to understand and overcome the reluctance of farmers to use computer-based tools designed to aid their decision making. As reported by Carberry et al. (2002) and McCown et al. (2009), we used a participatory action research approach with farmers, their public-sector advisers and private-sector consultants to see whether crop models could be valued by these practitioners as management tools when implemented in ideal circumstances. In FARMSCAPE (Farmers' Advisers' Researchers' Monitoring Simulation And Performance Evaluation), participants were provided with easy access to a versatile crop production simulator (Keating et al., 2003), local climate data, paddock-specific soil measurement for inputs, and direct personal support in creating value for practice (Dalgliesh et al., 2009; Carberry et al., 2009; McCown et al., 2009). The strategy was to create conditions of high relevance to management, to provide accurate simulation of situated performance, and to eliminate barriers related to data collection and computing. The core research aim was to test the persistent expectation of model developers that such models *should* be useful in managing climatic risk when implemented in such a supportive prototypic information system (IS). (The issue of the feasibility of sustained practical delivery of such decision support was judged to be secondary and deferred until experienced usefulness created a market. A system for

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doi:10.1016/j.agsy.2011.10.005

practical commercial delivery was later implemented as Yield Prophet (Hochman et al., 2009)).

This paper augments the evaluation of outcomes with evaluation of how our interventions influenced the cognitive ecology of participating farmers, public sector extension advisers, and private sector consultants (public sector participation declined to zero due to structural changes in extension). The focus here is on the interface between the largely-intuitive judgment and decision making of the user and an analysis-based IS. To evaluate an IS at this *cognitive* interface between observation and action requires drawing on theory from the behavioural sciences and humanities, guided by both our own experiences and our knowledge of the experiences of participating farmers and consultants. A theoretical framework designed for this purpose (McCown, 2011) is used to aid evaluation of FARMSCAPE IS interventions at a *cognitive* level. This evaluation complements and helps explain outcomes at the *action* level by comparing case experiences as narratives from evaluation interviews with what the cognitive systems framework indicates should be expected, given the situation.

The functional elements of the prototype IS included (a) production system simulation, (b) inputs of local climate records and soil data that enable the computer simulation to represent specific paddocks, (c) simulation outputs, (d) probabilistic analysis of outputs, and (e) a dialogic communication framework that supports production problem solving (Carberry et al., 2002). The two primary foci of IS intervention were (1) practical techniques for acquiring representative local soil information (Dalgliesh et al., 2009) and (2) flexible simulation of crop yields in paddocks specified using local soil and climate data (Carberry et al., 2009).

The first evaluation task uses the cognitive theory framework to explain surprises in adoption behaviour with regard to soil sampling and measurement. Initially there was surprising enthusiasm of farmers for soil measurements quite apart from their use in simulation (Dalgliesh et al., 2009). Later there was a surprising shift away from use of these technologies by participants who had earlier shown that they valued the innovations in their management, demonstrated high levels of understanding of the science, and championed use of the IS in farmer groups (Dalgliesh et al., 2009).

Attention then turns to evaluating the various ways the cropping systems simulator was used to reduce uncertainty in planning contexts about what to *expect* and what to *do*. The strategy of the What if Analysis and Discussion (WifAD) centres on assessing probable yield consequences of alternative courses of action given current soil conditions and many years of climate data.

The paper concludes with a discussion of the limitations of the notions of adoption and diffusion when the use of the technology results in learning that changes both mental models and develops the new ways that old tools and techniques can be used.

2. Evaluation methodology

To achieve our aim of finding through participatory action research if a simulation-based IS could be useful to farmers and advisers/consultants, we needed a means of evaluating *usefulness*. In keeping with our concern with the historical 'problem of implementation' of IS, our evaluation has featured a humanistic approach that captured practical values expressed by participants. FARMSCAPE evaluation took place in three phases. The first was a summative evaluation upon completion of the first 3 years of FARMSCAPE as a pilot project. This featured interviews with participants as groups – two groups of farmers and two groups of extension advisers and commercial consultants (Carberry et al., 2002).

The second phase was a 6 year period during which evaluation featured annual interviews with participants and members of other key stakeholder groups, providing a longitudinal structure for information. The evaluation was based on a constructivist approach. It sought to monitor and interpret the project through the eyes of the key participant groups: researchers; farmers; private consultants; and extension officers (both within and outside of the project) in a longitudinal study. At intervals throughout the project, interviews were undertaken with (approximately 30) representatives of these groups to capture learning and practice change as it happened and within the context of project activities and seasonal conditions. Interview data were collated and summarised from each participant group and returned to interviewees for checking that the information was correct. The project team received the summaries of all groups to provide an overview and stimulus for change in the project direction and activities (Coutts et al., 1998).

The third event was an ad hoc set of interviews of former FARMSCAPE participants, most of whom had been the most enthusiastic champions of our interventions. Of the 14 farmers interviewed, 12 had had no significant contact with the project researchers for 6–8 years. The other 2 had never had direct contact with researchers but were involved in monitoring and simulation activities initiated by their consultant who was, formerly, closely involved. In keeping with their preferences, five farmers were interviewed individually, and nine others with their local farmer groups (three groups). All farmers interviewed managed broad-scale cropping operations, with 12 of the 14 growing dryland cotton as a component of their system. Of the three consultancy firms represented, individuals from two were interviewed in company groups. The absence of any public sector advisers reflected the demise of this mode of advising in the public sector by this time.

The question sets for farmers and consultants were designed to fit their differing perspectives. Both sets focused on the themes of soil water storage characterisation and monitoring and, nitrogen monitoring and management, and the place of simulation modelling in relation to soil information. Although the main aim was to learn about the post-FARMSCAPE period, the opportunity was taken to capture the earlier experiences and retrospective interpretations of these at the time when interviewees encountered our interventions. They were also requested to do this against what they considered 'traditional' thinking and practice. The fact that the interviews were structured did not preclude spontaneous contributions or relevant unplanned questions. Sessions lasted 1–2 h, and by permission of the interviewees, all interviews were recorded, and later transcribed for analysis (Dalgliesh et al., 2009).

These interviews conformed closely to the theory/methods of the *episodic interview* (Flick, 2000): interviews were conducted with "natural groups"; the scientist-interviewers were primary actors in the earlier interactions and "speak the language" very well; there was a legacy of mutual understanding and high trust. Framed largely by two open-ended questions concerning their experience with the two main technologies comprising the FARMSCAPE IS, respondents were invited to relate their personal experiences and changes in views over time. Analysis of transcripts entailed abstracting the "plots" of the individual stories (Jovchelovitch and Bauer, 2000, p. 71) and relating plots to the expectations generated from the framework, given the conditions for the situation in question.

3. A cognitive systems framework

The cognitive systems framework of McCown (2011) forms a nested set of three figures—Fig. 2 represents an elaboration of the 'judgment'[1] element of the cognitive framework "map" in Figs. 1 and 3 elaborates 'probability' of Fig. 2 'analysis'.

[1] Throughout the paper, textual references to elements of figures are enclosed in single quotes.

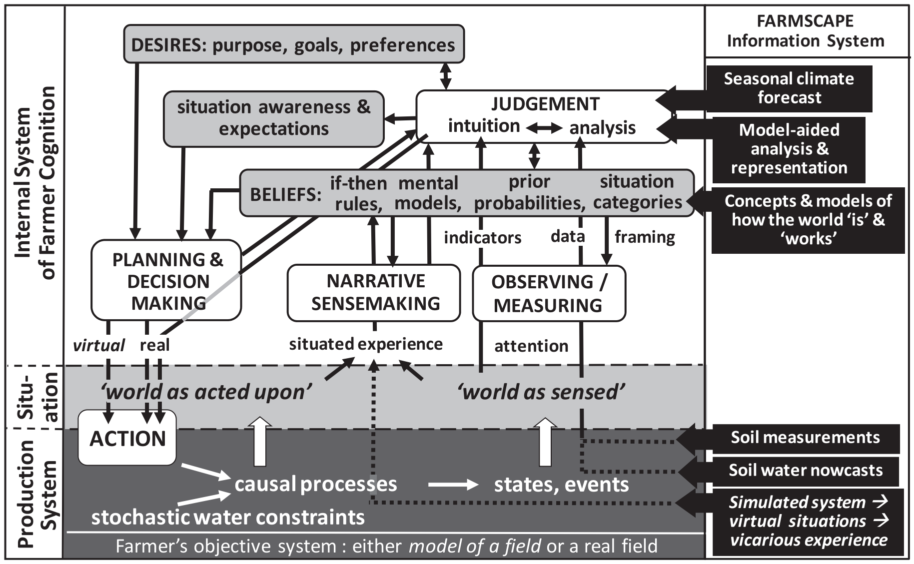

Fig. 1. An eclectic cognitive systems framework to aid thinking about intervention with an information system (IS) to support farmers' risk management in dryland cropping situations (McCown, 2011, Fig. 1).

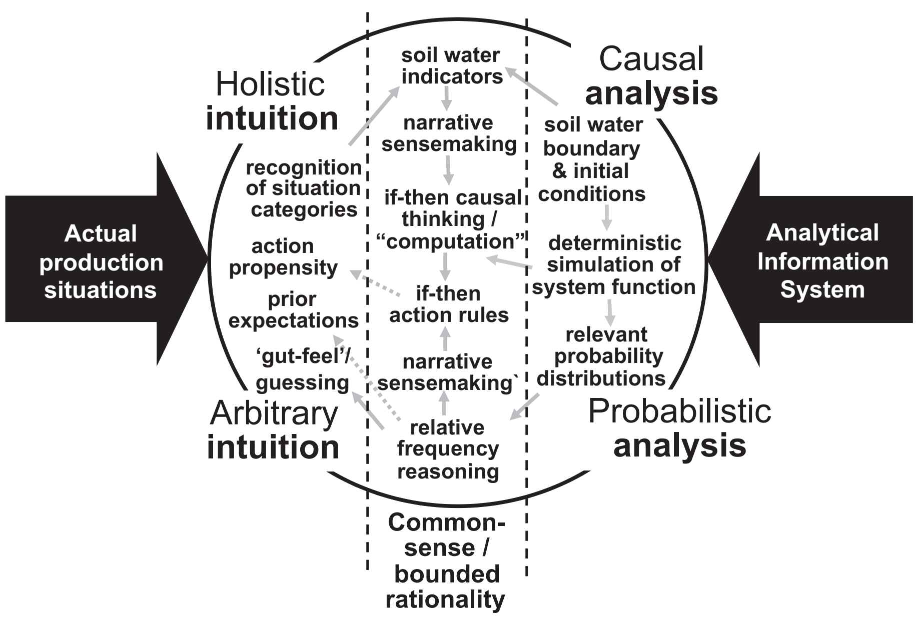

Fig. 2. A map of cognitive operations in 'judgment' in Fig. 1 on a continuum between intuition and analysis. IS = information system. (McCown, 2011, Fig. 2).

Fig. 1 includes (a) the farmer's cognitive processes in sensing/experiencing 'situations' and the thinking and learning that leads to 'action' in the 'production system', (b) the processes of a 'production system' in a highly uncertain climate that imposes 'stochastic water constraints' on 'states' and 'events', and (c) the researchers' 'Information System' prototype aimed at reducing management uncertainty. Due to the high uncertainty of the dryland cropping environment, 'planning' and 'action' must rely heavily on 'judgment' in shaping 'situation awareness' and future 'expectations'. The mode of 'judgment' changes between 'intuition' and 'analysis' in response to needs of the task or problem and to the nature of information coming from the 'situation', i.e. observed 'indicators' or measurement 'data' respectively.

In evaluating pre- and post-IS behaviour of farmers and consultants, this paper draws heavily on this theory that recognises that use of 'intuition' or 'analysis is a cognitive adaptation to the task or information environments. Fig. 2 looks inside 'judgment' at operations distributed along the continuum between 'intuition' and 'analysis'. On the vertical axis, 'intuition' varies between 'holistic intuition' associated with expertise and 'arbitrary intuition', or "gut feeling".

'Analysis' in Fig. 2 is of two sorts, 'causal' and 'probabilistic'. Fig. 3 elaborates on the problematic concept of probability, relating different probability concepts to their positions in Fig. 2, 'frequency' on the right and 'felt intuition' on the left.

4. Explaining surprising adoption behaviour regarding soil water measurement

4.1. The early surprise

Dalgliesh et al. (2009) reported on farmers' and consultants' experiences with the soil sampling and measurement technologies in the FARMSCAPE IS. There was a surprising readiness in both groups to adopt the analytic approach on offer. Very successful farmers confessed that they knew very little about the part of their farm below the soil surface and that this needed to change. Many farmers, either individually or in neighbourhood consortia borrowed, bought or built coring machines and acquired equipment for drying and weighing samples, as did most consultants. The enthusiasm of participants in these activities was sufficient to prompt research-funding organisations, quite early in the FARMSCAPE program, to initiate additional projects to take this technology beyond the intensive on-farm action research to a wider constituency (Carberry et al., 2002).

The reason for revisiting this history in this paper is to use cognitive systems theory to explain this surprising enthusiasm of farmers and consultants for analytic monitoring (Section 3, above; McCown, 2011). Of particular significance is Hammond's (1996) Cognitive Continuum Theory (CCT) indicated in 'judgement' of Fig. 1 and elaborated in Fig. 2. This theory posits that the mode of judgement (among a repertory bounded by the extremes of 'intuition' and 'analysis') needed to make sense of an uncertain 'situation' is "induced" by the "task environment" of the 'situation' and the nature of the information available (Fig. 1). Here, we postulate that change in 'judgement' mode toward 'analysis' was motivated by a felt need for increased accuracy, induced by changes in the task environment, i.e. the farming system becoming more capital intensive, less resilient, and more dependent on good decision making.

In an earlier cropping era, if a field was recognised as being in a situation category of "plantable", (Fig. 2, left), it was planted (Dalgliesh et al. (2009).

I-1 Farmer/consultant: It was a matter of having planting rain and you went for it. I was talking to Dad about this because he reckons we should have done some planting after recent rain. He said when they were farming they would have put some in without regard to how much stored moisture they had.

But with the intensive cropping that later evolved, where anticipated yield replaced crop establishment as the criterion, crop costs and financial consequences of failure increased, inducing more *analytical* judgements.

I-2 Farmer: It used to be the case that farmers' biggest constraint, as they would see it, is planting rain—planting events. These days, there's better appreciation that you're better off letting a lot of planting opportunities go by if you don't have sufficient soil moisture to give you a high probability of growing a viable crop. So that's totally different. Deferring the planting of crops has probably been some of the best decisions that this technology has given us.

I-3 Consultant: Fifteen years ago most decisions made here were based on planting rainfall events. If it rains you plant and then if you have a crop failure, bad luck. That's what it was like. But now we're saying we can't afford crop failures, how do we stop crop failures, and we start by relating crop failures to starting subsoil moisture. Back then we didn't have a strong appreciation of water use efficiency as in "so much soil water means this much yield". Because of that we didn't go after subsoil water. There's no point having one without the other. Then we got onto the "so many millimetres mean this amount of yield", "what's a break-even yield that's worth having a dabble at", and putting some things like that into perspective. For that we needed to determine what your soil moisture holding capacities are.

One of the indicators of movement from 'intuition' toward 'analysis' was dependence on intermediate technology indicated in Fig. 2 as 'soil water indicators'. This began while crop establishment was still the decision criterion, and focus was on the seed bed.

I-4 Consultant: You know there are still people around here that think, "I've had enough rain I'm going to plant." They haven't a clue what moisture they have in their soil. There are still a lot of farmers around that are like that – the older farmers, the older style. All they're concerned about is how can I get moisture in the seed zone to germinate. They use little screwdrivers to check.

But after the publication by Fawcett (1969) of the usefulness of a 1 m-long penetrometer, use of this home-made "push-probe" spread in the Northern cropping region. This is evidence of a shift on the cognitive continuum toward analysis and creating a favourable cognitive state for valuing a further move toward analysis using soil coring and measurement in FARMSCAPE. The push probe got farmers' attention beyond the seed bed to subsoil water. This was instrumental in the shift of focus from crop *establishment* to crop *yield* as the performance criterion.

I-5 Farmer: FARMSCAPE began at about the time we were starting to just use a push probe. Prior to that, we just had no feeling for water. We didn't even think that much about it or even understand it. Our soil monitoring was the traditional surface soil tests for nitrogen and other elements. Now we've gone right through seeing how important the whole profile is. It's just so logical when you think about it. We're now monitoring our soil profiles, particularly our good soils, annually.

I-6 Consultant: Although [with the push probe] we didn't have appreciation of water use efficiency as in millimetres mean this much yield, we did have a good idea of full and 1/2 full profiles and generally speaking that a full profile is going to be better for you.

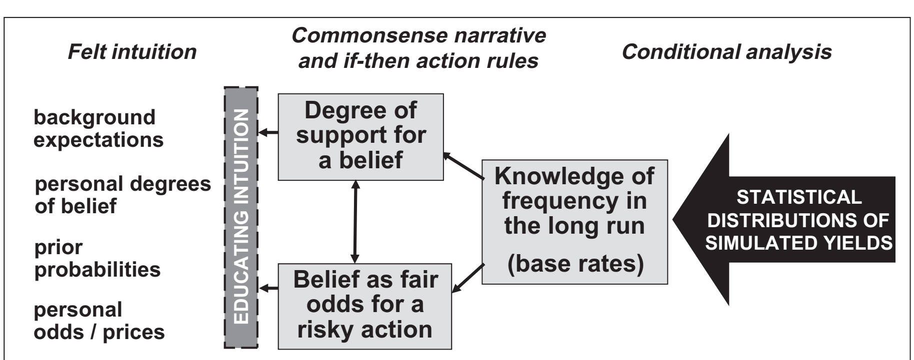

Fig. 3. A cognitive continuum of probability meanings. Shafer's (1992) three modes of probability as two types of commonsense beliefs stemming from knowledge of frequency, with IS as a source of objective conditional long-run frequencies. "Educating intuition" from Hogarth (2001). (McCown, 2011, Fig. 3).

The analytical intervention as FARMSCAPE 'soil measurement' (Fig. 1) depended on a qualitative change in a farmer's 'concepts & models of how the world is & works' (Fig. 1) that featured the soil as a "bucket" for water that was filled by rain and depleted by crop water uptake. Participants whose learning experience included construction of this new mental model (Fig. 1) were supported in their analytical judgement (Figs. 1 and 2) by the IS computer model which used bucket size, i.e. site-specific PAWC (plant available water capacity), and initial PAW (plant available water) and local daily rainfall data to simulate crop yield.

> *I-7 Consultant*: There is no point knowing how much water you've got in your profile if you don't know what it means to your risk profile, or your cropping potential, if you like. Knowing what that level *is* is one thing, but knowing what it *means* is another thing. [ ] That's where crop models come in.

4.2. A late surprise

The second surprise concerning farmers' soil monitoring behaviour came in the evaluation interviews several years after the FARMSCAPE project had ceased (Dalgliesh et al., 2009). The core sampling and quantitative measurement procedure that had been so readily adopted 10 years earlier was gone, replaced by simpler and cheaper methods. Economies included (1) less comprehensive sampling spatially in the paddock (fewer cores) and vertically in the soil profile (coring to lesser depth) and (2) substituting measurement of soil water content with 'soil water indicators' (Fig. 2) or with a 'soil water nowcast' (Fig. 1) provided by running the simple soil water balance model, HowWet (Dimes et al., 1996; Dalgliesh et al., 2009) using local daily rainfall.

One soil water indicator reported was the "look and feel" of soil in a core.

> *I-8 Farmer*: Now it's just a matter of look and feel. I started with [gravimetric] measurements and later just estimated squeezing the soil where it was wet.'
> Interviewer: 'Why did you change to look and feel?'
> *Farmer*: 'Just effort. It is a lot of work to get a good meaningful result by the time you've taken a core and split it up, dry it and weigh it and all that.

Another indicator of soil wetness involved a return to the push probe—but with a difference.

> *I-9 Farmer*: We've done a bit of a circle, really. Before FARMSCAPE we used to say 'we've got a foot or a couple of feet of water [i.e. wet soil]. With FARMSCAPE we cored and went and measured that through drying and that sort of thing. Now we sort of know what a foot – or 2 feet – is in millimetres of water. Before you didn't know what it was.'

'Soil water nowcasts' (Fig. 1) were used by a few of the farmers interviewed. However this option was most valuable to consultants, who, with clients distributed over a large area, made the greatest savings by sparing visits to the paddocks in question. A faxed or emailed notification by a farmer of recent rainfall at the site enabled a simulation that updated virtual soil water.

A consultant summed up the rationale for departures from the original FARMSCAPE techniques and indicated how information and insights gained in the earlier FARMSCAPE experience made this possible.

> *I-10 Consultant*: We've been doing this because it's very quick. [ ] We've found over time that knowing the soils at the start and knowing their upper and lower limits we can make some pretty good decisions quickly using cruder approximations of water actually there, at any point in time. You need a high degree of accuracy in the *decision* not a high degree of accuracy in *measurements*.

Significantly, no farmers interviewed had gone back to their old pre-FARMSCAPE intuitive approach. They had re-invented analytic soil monitoring by substituting to varying degrees available technologies that were simpler and more labour-efficient – a shift from *analytical* 'soil water boundary and initial conditions' to *common-sense* 'soil water indicators' (Fig. 2).

5. Crop models and the 'What-if' Analysis and Discussion (WifAD) meeting

5.1. Local farmer group meetings

In the main, FARMSCAPE interactions with farmers were conducted with pre-existing local farmer groups. Typically, a group of 5–15 local farmers meets periodically at a host farm for social interaction, discussions of relevant topics, access to invited experts, and conduct of learning projects, such as the soil monitoring reported by Dalgliesh et al. (2009). WifADs were conducted as invited contributions to farmer-hosted meetings and featured information exchange, simulation of relevant situations and scenarios, and discussion of implications for management. Typically, researchers joined meetings several times a year, with special effort made to coincide with the planning periods prior to planting both summer and winter crops. The primary aim was to make the FARMSCAPE analytical technologies of soil monitoring and yield simulation useful for practitioners' thinking about constraints and opportunities in their actual cropping situations.

5.2. The WifAD's origin in action research with farmers and advisers

When FARMSCAPE started, in order to the sensitive issue of farmer scepticism about models (McCown et al., 2009), the WifAD was initially avoided in favour of activities in farmers' fields, centred on soil water management and measurement and effects of soil water at planting on yield. Progressively, opportunity for simulation arose in the discussion of field results as questions of "what if we had done this last year?" or "how often would this outcome be expected?" The practical context of these interactions provided a dual opportunity for changing attitudes on simulation by (1) demonstrating the capability of the simulator to mimic the completed field experience and (2) extension of the experience to other recent seasons using the simulator with daily weather records. Here was a new way to enhance meaningful crop management "experiments" for initially-sceptical farmers.

But there remained the challenges of farmers making sense of probability distributions and then planning actions under high, but now known, uncertainties. The use of 'relevant probability distributions' required 'relative frequency reasoning' (Fig. 2) which is commonly employed by farmers. Instead they have a strong disposition to rely on 'narrative sensemaking' and 'if-then causal thinking' (Fig. 2) in keeping with management behaviour generally (McCown, 2011). However, the literature also provides convincing evidence that payoffs from using probability distributions can be high where uncertainty due to the innate randomness makes learning from experience difficult. Facilitation of 'relative frequency reasoning' became a central aim of the WifAD (McCown, 2011; Vick, 2002; Kahneman and Lovallo, 1993).

A challenge, we later learned, even for philosophers of probability, is the intrinsic difficulty of the concept of probability (McCown, 2011). In Fig. 3, what can alternatively be thought of as three types of probability or as three features of probability are depicted in relation to external and internal processes. 'Knowledge of frequency in the long run' is logically separated from the decision of what to do in a given situation, but influence on the action by knowledge of the distribution, albeit obscure, is not irrational.

> For the purposes of science and of everyday life, we need something that translates objective probabilities into rational expectations. This rule will take the relevant scientific probabilities and assure us, for example, that we can expect a chemical reaction to occur in a certain way, or that if we want to live long, happy lives, we really ought to consider giving up smoking. If no such rule is demonstrably rational, we are in serious trouble (Strevens, 1999).

Some problems were technical and led to important developments in the simulation software and in graphical representations of distributional outputs to largely-intuitive managers. But how farmers mentally processed these outputs was not adequately appreciated by the researchers for many years, and our eventual learning constitutes much of this paper and the framework of McCown (2011).

6. Evaluating different uses of simulation in WifADs

Over time, we found that simulations were being used in WifADs in several different ways. These included yield benchmarking, yield forecasting, tactical planning, scenario exploration (Carberry et al., 2009; Hochman et al., 2000), and virtual monitoring (Hochman et al., 2009), or nowcasting (Sharif et al., 2006). It is significant that these categories were originally created to describe the different directions farmers and advisers/consultants were taking this activity as their appreciation of possibilities grew and their experience accrued.

Along side this ongoing evaluation of our 'systems practice' was the evolving framework of 'systems thinking' through clarification of "what we think we are doing" in our analytical interventions (McCown et al., 2009). A step in this clarification was the appreciation that we were facilitating both *planning* and *learning* in activities in which the two are often difficult to distinguish. Exploring prospects of practical action in a WifAD is a computer-supported *thought experiment* in which learning often occurs.

6.1. Uses of simulation that support farmers' learning in thought experiments

Facilitation of practical learning in WifADs using science-based analysis needs to satisfy criteria of both meaningfulness to practice and analytical validity. Farmers need to be able to explore consequences of diverse possible actions taken in diverse possible soil conditions and to make sense of the diverse yield consequences imposed by the variable climate simulated from the historical daily climate records. In thinking and communicating about these uncertain matters, *probability* cannot be avoided. In Fig. 3, 'prior probabilities' encode 'personal degrees of belief', i.e. intuitive subjective probability. Frequency data are used to strengthen, update, or weaken the 'degree of support for a belief' (Pearl, 2000, p. 2) or sense of 'fair odds for a risky action'. Bayesian logic is ideally suited because it doesn't distinguish between subjective and objective (frequency-based) probabilities.

The central pillar of Bayesian analysis is conditional probability. Conditional probability is the probability of some event A, given the occurrence of some other environmental event or state, B. In Bayesian analysis, "conditioning" provides an avenue for prediction by generating a new distribution for only those values of a co-occurring when B has occurred.

> Conditioning is a passive way of "experimenting" with the system without imposing any values on the system variables or modifying the causal structure that produces the observations. One selects those instances of the system's output that produce a specified value (Druzdzel, 1993).

This "standard Bayes" approach relies on statistical correlation between the variable of interest and an environmental indicator variable. This non-interventionist, stratified sampling approach is the basis of the forecast of seasonal rainfall in a given SOI phase (Southern Oscillation Index) (Stone and Auliciems, 1992). But in analyses where criterion values are generated by structural equations of a simulation model there are significant benefits to using a "causal Bayes" approach (Pearl, 2000; Sloman, 2005). Instead of sampling, conditioning is achieved by intervention in the algorithms to "set" a causal effect via a condition, e.g. soil water at planning, or an action, e.g. amount of N fertiliser applied. This not only maintains the full size of the population of years, but it allows counterfactual, thought experiments.

> Although standard [Bayesian] logic does not distinguish between the *observation* of an event and the generation of the same event by an *intervention*, the distinction is central to causal Bayes. Causal models have the ability to represent both action (intervention in the world) and imagination (intervention in the mind) (Hagmayer et al., 2007, p. 92).

The power of the WifAD in exploring new possibilities relies on this generative (rather than correlative) attribute. This theory conceptually unifies past experience and learning in *imagination* in WifADs and learning from 'situated experience' in *action* in the paddock (Dalgliesh et al., 2009). Facilitating *learning* in WifADs can be construed as "intervention in the mind" *about* "intervention in the world".

6.1.1. Benchmarking

One type of thought experiment is useful to a farmer who, having grown a crop, asks "how close is this (achieved) yield to what was *possible* in these conditions?" When climate data and initial soil conditions are available, not only can the potential crop yield be simulated, but underperformance of the actual crop can often be diagnosed and opportunities for yield-enhancing management indicated. Benchmarking enhances learning as both formulation of expectations and understanding of causal processes.

> *I-11 Farmer*: Bench-marking has been probably one of the most important things. Looking back at the end of the season and saying "well we didn't achieve that, why is that so?" [ ] It's always interesting. We've sort of got away from thinking well maybe the model is wrong. I just sort of realised, we're saying well the model is the bench mark, and we're assuming it's right now.
>
> *Interviewer*: What has changed?
>
> *Farmer*: When you first see that new bit of technology, you are pretty sceptical to start with aren't you? I think there were some issues with it in the early days too that were identified. A lot of it had to do with soil characterisations and measuring your water as much as the model itself.

As a use of simulation, benchmarking is distinguished by its concern with the past rather than the future. Rather than being predictive, this activity is diagnostic, with yield as the condition, or symptom. The analysis uses the "causal" algorithms of the simulator to compute output from parameters, inputs, and initial conditions for a specific situation.

6.1.2. Scenario exploration

Analysis of a scenario is at the other end of the thought experiment scale from benchmarking. This type of enquiry "zooms out" from a single crop in highly specified conditions to bring the long-term history and the long-term future into scope. Simulation using long-term data provides a tentative "history of the future".

Like yield forecasting and tactical planning, scenario exploration generates outcomes expressed as probability distributions, but unlike these, interest is in the picture of the variation in yield that can be expected "in general" over the long term. Although commonly focused on shaping, in thought, expectations concerning a new venture, it is often appreciated for reducing ambiguity of expectations for an *existing* enterprise. Existing background expectations, or 'prior probabilities', formed in experience, are ambiguous due to a 'wicked' learning structure (Hogarth, 2001; McCown, 2011). One barrier to learning from experience in dryland farming is the long time-lags between action and outcome feedback that impairs associative learning. A second is random seasonal climate effects on yields that obscure action–outcome relations. Intervention with simulation and frequency analysis alleviates this "uncertainty about uncertainty" by, firstly, creating a 'kind' learning structure (Hogarth, 2001) by ordering past (simulated) events as objective 'frequencies in the long run' (Fig. 3). Farmers value this improved picture of climatic reality as new learning which replaces their intuitive prior probabilities with new analysis-enabled 'expectations' (Fig. 1).

A further benefit is provided when local, situation-specific information is used to "condition" these long-run expectations (Greening et al., 2005; Chandler et al., 1999). In FARMSCAPE in the Northern cropping region, conditioning on initial soil water storage (PAW) was of particularly high value to realistic scenario exploration (Dalgliesh et al., 2009; Carberry et al., 2009). Carberry et al. (2009) described a thought experiment that served as an analysis of causal sensitivity of PAW for this situation and demonstrated that PAW was of far greater predictive significance than the SOI.

> *I-12 Farmer*: I think the APSIM model has been the greatest benefit in helping farmers actually see what will happen in the long-term by using historical rainfall data and showing the importance of stored soil profile water.

Evaluations show that farmers strongly valued such WifAD scenario analyses even when they "confirmed what I already thought". According to theorists of cognitive uncertainty, such responses by expert managers should be expected. People are averse to ambiguity – they dislike not having information that they suspect exists.

> ...it follows that people will value provision of any information that reduces their ambiguity (or increases perceived competence), even if it will not change their decisions. This result is in sharp contrast to the economic model of demand for information, which assumes that demand for information is derived from its value in making decisions (Camerer and Weber, 1992, p. 358).

Scenario exploration led to profound changes in strategic thinking and production policy of farmers.

> *I-13 Farmer*: Ten years ago there was a bit of rotation – if you call wheat to barley a rotation, and then chickpeas came in. It wasn't a 'system' because we didn't know what we should be aiming for. We didn't really know what we were trying to achieve other than not to go broke. Out of each crop we weren't looking at it as a system. We didn't know what our resource potential was and we were in the drought, and I wanted to know why I got caught when other people had been able to plant and I hadn't. We were just doing things wrong when we started looking at [simulation]. We were focused on risky rainfall but found that soil was actually more important than climate in our area, with our soil type. We then went onto figure that our soils were potentially so good that we were under-shooting. Then, if you're going to go and throw that much fertiliser onto grow the perfect wheat crop that you can grow using the model, then you had to have a few other things right such as disease management and whatever else. One thing leads to another, and ends up with you trying to build a rotation. We've done those simulations using our soil type, looking at our climate and topography, and we built the system we've got now which is 4 crops in 4 years. I've changed my yield expectations. I've changed my rotation. I've changed my fertiliser strategies. I've changed my seeding strategies. I've changed my row configurations. My inputs have gone up. The profits have gone up. The gross margin per hectare has increased.

6.2. Uses of simulation that support farmers' situated planning and decision making

In scenario exploration, focus is on the role of good 'distributional' information for strategic learning and system design. In situated 'planning and decision making', analysis shifts from "histories of the future" to short-term prediction using conditional probability in yield forecasting and tactical planning. Analytical support has variously been structured by objective modes of either standard Bayes or causal Bayes theory and by the if-then causal "predictive propositions" of Beach (1992) concerning "what to expect" and "what to do", respectively.

6.2.1. Yield forecasting

We presume a farmer's intuitive predictive proposition for yield of a real or prospective crop can be represented as the conditional expression,

$$IF\ (crop,\ soil\ preconditions),\ THEN\ (yield\ distribution), \qquad (1)$$

with "built-in" influence of background knowledge, including 'prior probabilities' of yields (Strevens, 2006).

As an intuitive conditional yield forecast, this can be "supported" or "educated" in a WifAD by the analytical resources of a simulator, long-term climate records for the site, and initial soil conditions. The best estimate of future, unrealised, water-limited yield is a probability distribution based on the climate records of the past, conditional on preconditions, using causal Bayesian inferencing (McCown, 2011). In simulation practice, this commonly takes place as a yield forecast in which the model is incrementally run for a situation using real-time daily weather data until a point is reached where a forecast is desired. Commitment to a forecast has the effect of making the soil and crop variable values at this point in time *invariant* Markov preconditions for the probability distribution. The conditions on this date provide an invariant causal contribution to simulations of yield. Simulated future growth and yield is a function of these conditions and climate in each season simulated from daily records subsequent to the forecast date. Variability of yields among years is due to variation among years in the subsequent weather. A further "condition" is the point in the life history of the crop when the forecast is made, i.e. the proportion of the crop duration prior to the forecast date. The later the forecast the more reliable the prediction (Duchon, 1986; Potgieter et al., 2003), but the lower its forecast value for planning or control.

At about the same time that FARMSCAPE began, a new 'seasonal climate forecast' (Fig. 1) in the form of the SOI (Stone and Auliciems, 1992) became available as a precondition in Expression 1, above. The forecast uses a probability distribution based on the climatology and is conditional on the SOI. Skill of the forecast is measured by shift relative to the climatological base rate distribution (Hansen, 2002). These new probability distributions are potentially valuable if they enable the decision maker to better allocate resources between poor years and good years (Hayman et al., 2007). There were high expectations that the monthly phases of the SOI that correlate to rainfall in following months would enhance yield forecasting as decision support when used to condition probability distributions of long-term simulated crop yields (Potgieter et al., 2003), i.e. standard Bayes inference.

The strength of the forecast is represented in the difference in expectations between the climatological forecast that uses all years and the expectations based on the subset of years conditioned on the SOI-phase covariate at the time of forecast. FARMSCAPE evaluation interviews in the Northern Cropping Region have found that (a) the forecasting of yields in WifADs have been of low value to farmers compared to other uses of simulation and analysis and (b) that soil water at planting is a better predictor of yield outcomes than the SOI phase in this region where cropping relies so heavily on stored water in deep clay soils.

> *I-14 Farmer*: We're dealing with a lot of variabilities, but the climate is really the biggest one. We've been through scenarios when we haven't got a full profile. What are the best options? We've seen that on the model and we've even had the practical experience with it. We've seen the scenarios where we do have a full profile at the start of a dry year or it's come a wet year or whatever. It's more important than seasonal outlook [SOI phase] by a mile on our soils because our soils store so much water.

A similar view was expressed in the interview response of a farmer when asked (in 2002) about the value to his tactical planning and decision making of knowledge of the current SOI phase. This farmer's first pass at answering the question makes the point that the value is not mainly in the SOI as a tactical forecast. More important was the learning from simulation used in evaluating the SOI that other preconditions in Expression 1 above were more predictive, e.g. soil water storage.

> *I-15 Farmer*: Once you've done the model runs you can sort of think of the application of the results in new situations as they come along. We did a lot of that work back in '92, '93 drought when the SOI was terrible and I distinctly remember the model runs we did on a sorghum planting in September with, I think, 40 cm of moisture [depth of wet soil] versus a sorghum plant in December. I still remember those model runs and how the December one still came out better simply because of the chance to store more moisture in a prolonged fallow period. That comes back to you.

In a second pass at the question, the farmer acknowledges that there is some benefit from paying attention to the current SOI signal.

> *I-16 Farme*: [The SOI is] useful in just trying to pick the years to "go for broke" and the years to pull back and take the conservative approach. When they're talking El Nino and when you're seeing the SOI hang consistently at minus 10, you know it's not the year to go and double crop or go and plant that paddock with only 30 or 40 cm of moisture [depth of wet soil]. You just don't do it. It's cheaper to go to the coast and spend it on a holiday. When you've got a rapidly rising SOI phase and you can sort of see that in the last 3 weeks every weather change has had rain in it, you think, "hang on, let's just take a bit of a punt". Its value is in indicating when to "go for it" and when not to.

6.2.2. Tactical planning

Tactical planning in WifADs is testing with the simulator the feasibility of *alternative actions* whose outcomes depend largely on an uncertain seasonal climate yet to be realised. Here, a what-to-do proposition is a what-to-expect proposition in which the actor intervenes (in imagination in what-if planning) in an attempt to cause a desired state of affairs. The basis of an intuitive predictive proposition of a farmer is a largely experiential understanding of 'the world as acted upon' (Fig. 1) that links knowledge of the current situation state and a desired future state or goal. This can be modelled as the conditional statement:

$$IF\ (crop,\ soil\ preconditions),\ IF\ (action),\ THEN\ (yield\ distribution) \quad (2)$$

Support in WifADs for farmers' "what-ifs" concerning the consequences of specific actions and comparisons of outcomes of alternative actions parallels that described for yield forecasting, above. For a real-time decision situation with known preconditions, a specified *action* is applied to the soil/crop data, i.e. the invariant causal Markov soil condition on that date for generating the conditional probability distribution from simulated historical seasons. Alternatively, when a what-if enquiry involves a conditional rule-, a modified intervention is used. For example, the (simulated) action of planting a crop is initiated by satisfaction of the conditions of a rule for seedbed wetness and subsoil stored water. Because this rarely involves the "here" and "now", the planting rule is allowed to operate in response to the climate inputs of the simulation. This means that "date" is not part of the invariant condition for triggering planting action hypothetical WifADs.

The distinctive aspect of a WifAD for tactical planning is that although a farmer's what-to-do predictive proposition is implemented in the simulator to achieve the best yield prediction possible, interest here is not primarily in this uncertain forecast, but in what is the *best action* in the face of this uncertainty, i.e. the best gamble. By ordering the simulation outputs of *alternative* feasible actions, the action with superior outcome performance can be identified, with seasonal climate variability remaining in the background. In the decision sciences, this strategy is formalised as stochastic dominance analysis and is used to order uncertain actions according to the stochastic efficiency of their cumulative probability curves as an aid to identifying the most *risk-efficient* action (Anderson, 1974). In FARMSCAPE and Yield Prophet, this approach is used with representations such as Fig. 5 in Carberry et al. (2009) and Figs. 3 and 4 in Hochman et al. (2009). Graphically, the stochastic superiority of an action is proportional to the degree its cumulative probability distribution is displaced to the right of another. Farmers have appreciated the logic of this pictorial representation, and it became part of the WifAD discourse as farmers' interpretation experience accrued.

An important type of tactical practical planning concerns 'go/no go' decisions (Vick, 2002, p. 380) where the actions being compared are mainly a matter of timing, and timing is mainly a matter of when required conditions are most nearly and/or most likely to be satisfied. Appropriating the empty what-to-do predictive proposition (Expression 2) consequent soil conditions simulated after an early 'no go' planting decision become new preconditions for possible later planting actions. A valuable intermediate output, obtained through this repeated simulation, is the frequency with which conditions more favourable to high yields will be achieved by delayed planting.

> *I-17 Farmer*: The [planting] opportunity might have only come very late. Climatic outlook is disastrous due to an El Nino. Soil only wet down to a foot after a long fallow. We get planting rain in mid to late July and we say "no, we're walking away from that." Because you know that in this area we can wait just a few more months to end of September/October and plant a summer crop. By then you've possibly accumulated a little bit more soil water. [ ] We've never ever regretted not planting the paddock. We did it last winter. The planting opportunity came real late. There was a bunch of growers around here went

out and planted wheat. Pretty well all the crops failed because it just didn't rain again.

The flexibility of the simulator in enabling a wide variety of tactical planning analyses and discussions came to be seen by FARMSCAPE scientists as the key to the continuing interest and enthusiasm of farmers, consultants and funding organisations for the WifAD as decision support. It was largely around this capability that the commercial service to crop producers and their consultants, Yield Prophet (Hochman et al., 2009), was designed. But it wasn't until much later that another significant impact of using simulation in the tactical planning mode was discovered.

7. The 'if-then action rule'

7.1. Another surprise

FARMSCAPE "alumni", comprising farmers and consultants who had been very active and creative in their participation before the project shifted to other regions, were re-assembled to record stories of the early experiences and what had been happening since the researchers left (Dalgliesh et al., 2009).

I-18 Interviewer: You haven't done much simulation here over the last few years. Is that a service you would still see of benefit to you or have you gone past that?
Farmer A: From that experience [with the simulator] we can put some numbers on it and even predict some of the outcomes in the normal type seasons. We now have rules of thumb about planting dates for wheat or sorghum. Yields will decline after a certain date and we know the effect of more starting moisture. We can sort of generally know and predict the outcome. There is still a place for simulation when you've got a planting situation out of the ordinary. This season will be a classic I suppose. Sorghum versus corn at the end of December when it finally rains, or some choice like that. Moisture is this, SOI is that. Just when you get out of the normal system there's still a place for it.
I-19 Interviewer: I get the impression from what you're saying that soil monitoring is the routine part of your process these days? Simulation is something you would do if there is an issue that comes up that needs a little bit of further investigation.
Farmer B: That's a fair comment. The thing is we never know at the beginning of the season exactly how it's going to rain. If you did and knew exactly how things were going to run, maybe modelling everything every time would give you some benefit that would be worthwhile. But those early simulations are still valuable. We've been through scenarios if we haven't got a full profile. What are the best options? We've seen that on the model and we've even had the practical experience with it. We've seen the scenarios where we do have a full profile at the start of a dry year or it's come a wet year or whatever. It's more important than seasonal outlook by a mile on our soils because our soils are so good. We've sort of got some of those things. We are looking at them in a different way, but we've had the experience. I don't think you need to go back and do all of that every year. You tend to remember most of those main important things.
I-20-Interviewer: How important has the information you've got out of simulation been to what you do?
Farmer C: It's been critical. That's how we designed our rotation. I think it's good for "what ifs". It's not perfect. It doesn't replace management. I think you can design systems that are robust. You can do a lot of "what ifs", what's my risk potential, but it's not perfect. If you design a good robust system, it's right for a wet year and for a dry year. If you haven't, you haven't got a good system. That's what we're finding out about the system we designed. By just putting some critical rules in there, I think you can design a very good, very safe, very robust system.

It became clear from these interviews that simulation was still highly valued by farmers as virtual experiments concerning 'plausible promises' (Douthwaite, 2002, p. 218). The results gave them experience and stories of conditions, actions, and outcomes which they sometimes reinvented as simple rules for action. They now used these rules to guide risk-efficient responses to conditions, especially to the state of stored soil water. In the face of irreducible climatic uncertainty, 'if-then action rules' that originated in 'analysis' replaced 'arbitrary intuition' (Fig. 2). As concluded by a noted management scientist,

"…managerial action is rule-based gambling…meaning that the manager does not simply toss a coin but instead uses rules or guidelines as best as possible" (Isenberg (1986, p. 258).

7.2. Explaining WifADs' facilitation of if-then action rule construction

'If-then rules' (Fig. 1) were formulated over time through 'narrative sensemaking' from 'vicarious experiences' in tactical planning WifADs. In the interactive analysis at the centre of the tactical planning WifAD, there is a dynamic process of shifting attention between what to expect and what to do, beginning with a what-to-expect probability distribution of outcomes of an action that is both intuitively plausible and promising. In a glamorized way, yield distributions for alternative actions/crops for a given situation with specified soil conditions could be graphically compared across all years and the most risk efficient action overall identified. Conditional rules, e.g. IF (date range, soil conditions) THEN PLANT (crop species, cultivar) AND FERTILISE (fertiliser type, amount), were formulated.

The resulting 'if-then action rule' can be seen as a product of experience in a learning structure rendered "kind" by the analysis process (McCown, 2011; Hogarth, 2001). The final action rule is a causal if-then *deductive* rule, even though the analysis is probabilistic. A simple 'if-then action rule' resolves what-to-do ambiguity and provides the user with confidence that although variability in yield outcomes will be experienced, risks would be higher with any alternative action (as far as is presently known). It is seen by a farmer as the "best bet" in the circumstances.

Evaluation interviews of farmers and consultants provided examples of the utility of using 'narrative sensemaking' processes in WifADs to make 'commonsense' simple rules (Fig. 2).

I-21 Consultant: There is no point knowing how much water you've got in your profile if you don't know what it means to your risk profile or your cropping potential if you like. It's knowing what that level *is* is one thing but knowing what it *means* is another thing. [ ] That's just where APSIM and other forms of crop models come in. We've done WHEATMAN[2], we've done all those different ways, and freehand ways of calculating in terms of water use efficiency [WUE = mm water to produce 1 kg grain]. Now we've got all that down in a series of best bet rules if you like, so that we don't have to re-assess that every time we want to make a decision. We've already calculated that.
This gets you into this risk analysis, and we say the worst thing you can do is grow a failed crop, because not only do you lose money on that crop but you then upset the next one. What farmers need to know is at what point do they actually make a profitable crop in terms of millimetres of water? That's the added dimension to making a risk analysis or a risk decision on whether we do or we don't plant. Out here it's often been

[2] Woodruff (1992).

the case that farmers' biggest constraint, as they would see it, is planting rain, planting events. Now there's better appreciation that you're better off letting a lot of planting events go if you don't have sufficient soil moisture to give you a high probability of growing a viable crop. So that's totally different.

I-22 Farmer A: Not planting crops has probably been some of the best decisions that this technology has given us. [ ] We've never ever regretted [deferring] planting the paddock. We've been willing to walk away from planting our crop. I think even at the moment we went into this season on limited moisture in a lot of paddocks and we made a decision not to plant a summer crop in the first rain. We just said ''hey it's too risky''. There's 30 cm of moisture [depth of wet soil]. The neighbours next door were out putting on fertiliser and ploughing enough fence to fence ready to go. We said forget it. We're not going to plant until we've got at least 60 cm–70 cm on it to go into sorghum and more for cotton. It's great to be able to make a decision like that and walk away in confidence that you know that it's been calculated.

It is evident that these action rules derived from what-to-do farmer thinking in light of situated what-to-expect analysis serve to greatly reduce the ambiguity imposed by the climate. But farmers made it clear that while analysis-based rules can improve responsive strategic *design*, they are no substitute for the 'holistic intuition' that enables day-to-day risky *management* (Fig. 2).

I-23 Farmer C: But it still doesn't replace *management*. I don't think you can get cute with it. I think what it can do is show you potentials. It's a tool. Once you sit down and logically think out doing several runs, you can refer back to those runs and they're pretty consistent across crops. [ ] It gives you a really good skeleton to work from and you build a good system. No one has the time and no one has access to the bloke with the time to be able to do the really cute stuff. That's not where the big gains are for agriculture.

8. Discussion

This paper provides an answer to the question ''How might scientists' models and analytical methodology provide value to farmers' practice that is largely intuitive?'' But the title also commits to an explanation as well, and Fig. 2 can be seen as a rough map to guide this. Most basically the figure maps a continuum between 'intuition' and 'analysis', with an intermediate set of cognitive behaviours in a class that Hammond defined as 'commonsense' (Fig. 2).

As used here, ''common sense'' refers to the cognition that is as analytical as it can be and as intuitive as it must be, or the converse, depending on the inducement from task conditions. That is, one is as rational (or intuitive) as one can be, needs to be, or is induced to be in each task situation. When the limit of one's rationality is encountered, one begins to draw upon intuitive cognition, and vice versa (Hammond, 1996, p. 150).

Fig. 2 also maps effects of intervention with an IS to support 'analysis' when task conditions in the 'actual production situation' make it attractive or at least potentially attractive. Implicit in the oscillations around 'commonsense', above, are the attributes that respectively characterise 'intuition' and 'analysis', i.e. *simplicity* and *complexity*, with practical implications for personal economies of attention, time, mental effort, etc. In the normal state of the production situation, ''simplicity'' characterises the automatic processes of 'intuition'. At the 'analysis' pole of the continuum, adoption of the IS implies acceptance of complexity along with accompanying data baggage. Yet, we have seen from interview narratives that learning facilitated by the FARMSCAPE IS *did* indeed take place. What follows here is an attempt to interpret the often subtle and indirect outcomes of this decision support intervention as a paradigm shift. The focus shifts from design and delivery of products and derived information to using analytical science to facilitate different kinds of personal learning that contribute to better functional understanding of the production system, reinvention of intuitive heuristics, and the development of self-directed learning of decision makers.

Intuitive practitioners were motivated to engage with the IS to explore the possibilities that they were missing a significant opportunity for managing risk. Taking the simulator to farms, together with techniques and resources to model water in local soils, provided a prototype IS to present to farmers as a 'best bet' tool for exploring climatic risk management possibilities. The surprising level of interest we found can be interpreted as the adoption by farmers and their advisers of a Douthwaite's *plausible promise* of benefit. But to actually achieve the benefit of the plausible promise, this shift from 'intuition' to 'analyses' in Fig. 2 required the coincidence of two non-trivial beliefs.

The first was a sense of increasing threat from seasonal climate variability to the increasingly vulnerable farming system. At the time of this project, the industry was still adapting to a trend away from a tradition of mixed crop-livestock systems to continuous crop-fallow systems with opportunistic inclusion of both winter and summer crops.

The second requisite belief was a new mental model for soil water and its control of production that opened up new possibilities for soil water 'awareness' and for water-limited crop yield 'expectations' (Fig. 1). The soil profile water balance model used in the simulator to constrain crop growth was communicated and readily appreciated using a 'bucket' metaphor (Dalgliesh et al., 2009). The key learning contribution was how to take advantage of information in the environment that *could* be known but rarely *was*. Even though the uncertainty of climate was large and irreducible, the residual predictive power of soil water information, frequently of critical importance in this region, was being largely ignored. Farmers who previously had not thought of the soil as a ''bucket'' came to appreciate that greater attention to how much soil water was ''in the bucket'' at planting had 'plausible promise' for actions and yield expectations that they had been ignoring (I1). The change was from a simple intuitive soil surface wetness model to a relatively complex water balance model for a multi-layered soil profile. This shift toward analysis on the continuum in Fig. 2 was ''pushed'' by the desire to understand and predict production-relevant change in soil water and ''pulled'' by opportunity offered by the availability of the IS for novel measurement procedures and computations.

In addition to a new way of thinking about soil water, accepting the complex analytical approach meant coming to value the simulator's computations as (mostly) reliable grounds for expectations of yield outcomes. Carberry et al. (2009) described the validation exercise that rehabilitated the originally-prevalent ''toys for scientists'' attitude toward models. In its place emerged an expectation that the simulator *can* be accurate when based on good site data and appreciation that the need for a client to develop skills for knowing how much trust is warranted in a particular case (I-11, I-12).

In this recapitulation of a learning journey motivated by a plausible promise that analysis could aid discovery of opportunities for reducing risk, farmers and consultants at this point are equipped with (1) access to and confidence in a simulator and (2) access to soil and climate data required to mimic 'actual production situations' of interest or other relevant hypothetical situations. The WifAD can now serve as a ''management flight simulator,'' or ''learning laboratory'', for benchmarking yields, analysing scenarios, yield forecasting and tactical planning (McCown et al., 2009; McCown, 2005).

In principle, appreciation of the analytic approach is most readily achieved in *benchmarking* where the climate data over the course of the production event can be input, and interpretation is explanatory rather than predictive. But irreducible uncertainty about the future remains.

Simulation facilitates *scenario exploration* by providing base rate yields at a site for nominated hypothetical situations (soil conditions and contemplated actions) as grounds for expectation of variation over an indefinite future based on simulations using historical climate records. It answers the question, "What can I expect over the *long term* if I do "x" under "y" conditions at this site?" The analysis quantifies uncertainty but doesn't reduce it. The contribution of analysis is in providing objective odds for local farming gambles. This mode of support is analytically robust and universally appreciated by farmers and consultants as providing valuable "ecological" learning and a tool for making adaptive structural changes (I-13).

Simulations to provide *yield forecasts* answer the question, "What can I expect *in the pending season* if I do x under y conditions at this site?" The analysis returns an appropriate yield probability distribution, but the decision maker is left, at the time of decision, with irreducible uncertainty due to each pending season being a random sample of the distribution. A central aim of the research was to learn if farmers found base rates of simulated site-specific yields of value for decision in an individual season. Early in the project, some farmers imagined this as a potential forecasting tool in forward selling of crops, but it soon became clear that the seasonal variability is too high for the median to be an adequate forecast of yield in a particular season. The El Nino Southern Oscillation (ENSO) with the seasonal forecasting instrument of the SOI phase provides opportunity for reduction simple risk. While substantial improvement to a forecast can sometimes be achieved, such improvement is highly variable. "Emphatic" forecasts can be expected less than half the time due to indeterminate states in the underlying meteorology (Meinke et al., 2003). Farmers learned from the simulations and analyses that the forecast value of initial soil water was far greater in this region than the SOI (I-14), but the SOI had value as a coarse indicator (I-16).

Whereas scenario exploration and yield forecasting both concern the task of reducing what-to-expect uncertainty, the core task of *tactical planning* is deciding what to *do* this season, given present conditions. The analysis proceeds by combining analyses of scenarios for different feasible action(s) given the initial conditions. The comparison criterion is typically the probability of exceedance graphs for all seasons in the record. Multiple distributions are compared on a single graph, and farmers became skilled in using this pictorial means of identifying the most risk efficient action across all years. It was clear that farmers were finding this analysis useful in their decision making. To the scientists, situations specified for analysis with soil water, soil N, date, crop, cultivar, etc. indicated a uniqueness of situations that warranted a timely decision support service in meeting farmers' future needs. Farmers, on the other hand, tended to focus on the dominant conditions of situations, i.e. soil water, date, and crop. Only years later in interviews did the researchers learn that the predominant farmer strategy for "future proofing" was to use successive, timely, WifADs in the project to construct simple 'if-then action rules' (Figs. 1 and 2) that were applicable in every season. The high farmer interest in timely tactical planning WifADs during the several years of the project supported the researchers' interpretation that post-project analytical support for tactical planning could be provided as a timely service. Indeed, in the project team's expansion of activities to other geographic regions, such a service has been established (Hochman et al., 2009).

The four types of analyses emerged from early WifADs as scientists' names for categories of participants' visions of 'plausible promises' for their management using this IS technology (Hochman et al., 2000; Carberry et al., 2009). Over time, the prototyping of a customised service to *deliver* these 'plausible promises' (by commercial providers) became the focus of the research. But 5 years or so after the end of several years of intensive work, the outcomes proved to be quite different. Our evaluations centred on questions of "what value" for management was provided by the prototypic IS. The results revealed that instead of a market for a complex, but customised, analysis, farmers had opted for the simplicity of DIY customised 'soil water estimates' with narrative that reasoned the causal connections to new simple action rules (Fig. 2). Of those interviewed, gravimetric measurement of soil water in the IS had been largely replaced by a variety of simpler/cheaper/quicker techniques, many of which had been used prior to FARMSCAPE participation. But, significantly, there was no indication of reversion to the earlier 'simple' intuitive indicators for 'recognition of situation categories'. Instead, new value was gained for simple devices by calibrating them against more accurate and costly complex measurements (I-9). For some, a compromise of accuracy and economy was achieved by retaining analytical soil coring but reducing the number of increments and/or in cores per unit area. Sometimes an estimate of soil water was used in "if-then computation" of yield; sometimes it was used to condition an 'if-then action rule' (Fig. 2).

This learning that moves cognition back toward *intuition* is the outcome of tests of 'plausible promises' of benefit from different modes of analysis. Instead of confirming an ongoing market for a consulting service based on such analyses, farmers and consultants in this region were indicating that practical dryland farming did not offer a suitable environment for them to depend on such relatively costly and complex *computed* rationality, as it appears to be doing in other regions (Hochman et al., 2009). But this did not mean they reverted back to their pre-FARMSCAPE practices. Their discovery that they could derive substantial benefits using their insightful mental models even when the task conditions were pragmatically limited by quick and cheap estimation methods and simple action rules-of-thumb was what Herbert Simon called *bounded rationality*. In interpreting Simon, Hammond wrote,

> [As opposed to the computed rationality in WifADs,] "Bounded rationality" means that cognitive activity has neither the time nor the resources to explore, and examine, or contemplate fully and completely the "problem space" of the task. The problem space that is explored, however, is explored in a rational or analytical fashion. Thus, rationality continues to be employed; it is simply "bounded," or limited by task conditions (Hammond, 1996, p. 166).

Hammond was calling attention to a conflict between Simon's concept of 'bounded rationality' and his own concept of 'commonsense' as intermediaries in cognitive processes between intuition and analysis (Fig. 2). For Simon, once complex 'computed rationality' is *understood*, as a new mental model, the pragmatism that restricts 'analysis' to only a part of the problem space is imposed only by the bounded task conditions, forcing *satisficing* rather than optimising to alleviate what-to-do imperatives. The close correspondence of our experience with Simon's theory means that we pragmatically proceed from this point using 'bounded rationality' as a replacement for 'commonsense' (Fig. 2). Movement on the cognitive continuum toward analysis is induced by felt task need for analysis *plus* a new analytical mental model that better supported analysis. Movement in the opposite direction, toward intuition, is induced by an interpretation of the task in which satisficing provides a "good enough" solution.

At the time, our intervention with an analytical IS was seen by many as violating the progressive idea that impact on farmer behaviour depended on facilitation of appropriate knowledge construction. The argument was that we should be presenting *simple* tools and demonstrations derived from our scientific analytical models to our practitioners. Our counterargument at the time was that this risked depriving participants the discovery learning at the core of action research that our models were equipped to facilitate and farmers keen to experience. In other words, complex models are able to facilitate learning that takes into account key soil characteristics, histories of random seasonal climate variability, and 'plausible promises' of systems innovations yet untried. After that learning, it is now clear that the premium for judgements and decisions switches to satisficing that avoids jeopardising attainment of the plausible promise of benefit in practice.

This surprising learning pathway that goes from the simplicity of intuition to the complexity of analysis and partway back toward a new enlightened intuition brings to mind a reference by Hayman and Easdown (2002) to a claim by the eminent US Supreme Court Justice and practical philosopher, Oliver Wendell Holmes' that

> "I don't give a fig for simplicity this side of complexity, but I would give my life for simplicity the other side of complexity."

Acknowledgements

The authors of this paper have been the key participants in the FARMSCAPE team and acknowledge the support of CSIRO as an organisation willing to support this applied systems research effort. FARMSCAPE projects have gained a wide support base, most notably from Grains Research and Development Corporation. The many farmers and agribusiness advisers involved in FARMSCAPE projects have been enthusiastic and vital participants. They are too numerous to name but their influence and support has been immense and we thank them for all the opportunities and learnings they provided to us.

References

Anderson, J.R., 1974. Risk efficiency in the interpretation of agriculture production research. Review of Marketing and Agricultural Economics 42, 131–184.
Beach, L.R., 1992. Epistemic strategies: causal thinking in expert and non-expert judgment. In: Wright, G., Bolger, F. (Eds.), Expertise and Decision Support. Plenum Press, New York, pp. 107–128.
Camerer, C.H., Weber, M., 1992. Recent developments in modeling preferences: uncertainty and ambiguity. Journal of Risk and Uncertainty 5, 325–370.
Carberry, P.S., Hochman, Z., McCown, R.L., Dalgliesh, N.P., Foale, M.A., Poulton, P.L., Hargreaves, J.N.G., Hargreaves, D.M.G., Cawthray, S., Hillcoat, N., Robertson, M.J., 2002. The FARMSCAPE approach to decision support: Farmers', advisers', researchers' monitoring, simulation, communication, and performance evaluation. Agricultural Systems 74, 141–177.
Carberry, P.S., Hochman, Z., Hunt, J.R., Dalgliesh, N.P., McCown, R.L., Whish, J.P.M., Robertson, M.J., Foale, M.A., Poulton, P.L., van Rees, H., 2009. Re-inventing model-based decision support with Australian dryland farmers. 3. Relevance of APSIM to commercial crops. Crop & Pasture Science 60, 1044–1056.
Chandler, C.C., Greening, L., Robison, L.J., Stoppelbein, L., 1999. It can't happen to me. or can it? Conditional base rates affect subjective probability judgments. Journal of Experimental Psychology: Applied 5, 361–378.
Coutts, J.A., Hochman, Z., Foale, M.A., McCown, R.L., Carberry, P.S., 1998. Evaluation of participative approaches to RD&E: a case study of FARMSCAPE. In: 9th Australian Agronomy Conference. Agronomy – Growing a Greener Future', Wagga Wagga (July 1998).
Dalgliesh, N.P., Foale, M.J., McCown, R.L., 2009. Re-inventing model-based decision support with Australian dryland farmers: 2. Pragmatic provision of soil information for paddock-specific simulation and farmer decision making. Crop & Pasture Science 60, 1031–1043.
Dimes, J.P., Freebairn, D.M., Glanville, S.F., 1996. HOWWET? A tool for predicting fallow water storage. In: Proceedings 8th Australian Agronomy Conference, pp. 201–210. <http://www.regional.org.au/au/asa/1996/contributed/207Dimes.htm> (accessed 16.12.08).
Douthwaite, B., 2002. Enabling Innovation: A Practical Guide to Understanding and Fostering Technological Change. Zed Books, London.
Druzdzel, M.J., 1993. Probabilistic Reasoning in Decision Support Systems: From Computation to Common Sense. PhD Thesis, Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA.
Duchon, C.E., 1986. Corn yield prediction using climatology. Journal of Climate and Applied Meteorology 25, 581–590.
Fawcett, R.G., 1969. Soil Moisture Probe for the Wheat Belt of Northern New South Wales and Southern Queensland. North West Wheat Research Institute, Report No. NA 69/2, Narrabri, NSW.
Flick, U., 2000. In: Bauer, M.W., Gaskell, G. (Eds.), Qualitative Researching with Text, Image, and Sound: A Practical Handbook. Sage, London.
Greening, L., Chandler, C.C., Stoppelbein, L., Robinson, L.J., 2005. Risk perception: using conditional versus general base rates for risk communication. Journal of Applied Social Psychology 35, 2094–2122.
Hagmayer, Y., Sloman, S., Lagnado, D., Waldmann, M.R., 2007. Causal reasoning through intervention. In: Gopnik, A., Schultz, L. (Eds.), Causal Learning: Psychology, Philosophy, and Computation. Oxford Univ. Press, Oxford, pp. 86–100.
Hammond, K.R., 1996. Human Judgment and Social Policy: Irreducible Uncertainty, Inevitable Error, Unavoidable Injustice. Oxford Univ. Press, Oxford.
Hansen, J.W., 2002. Realizing the potential benefits of climate prediction to agriculture: issues, approaches, challenges. Agricultural Systems 74, 309–330.
Hayman, P.T., Easdown, W.J., 2002. An ecology of a DSS: reflections on managing wheat crops in the N.E. Australian grains region with WHEATMAN. Agricultural Systems 74, 57–78.
Hayman, P., Jason, C., Mullen, J., Parton, K.A., 2007. How do probabilistic seasonal climate forecasts compare with other innovations that Australian farmers are encouraged to adopt? Australian Journal of Agricultural Research 58, 975–984.
Hochman, Z., Coutts, J.A., Carberry, P.S., McCown, R.L., 2000. Cow up a tree: learning and knowing processes for change in agriculture. Case studies from industrialised countries. In: Cerf, M., Gibbon, D., Hubert, B., Ison, R., Jiggins, J. Paine, M.S., Proost, J., Roling, N. (Eds.), INRA Editions, Versailles Cedex, France, pp. 175-188.
Hochman, Z., van Rees, H., Carberry, P.S., Hunt, J.R., McCown, R.L., Gartmann, A., Holzworth, D., van Rees, S., Dalgliesh, N.P., Long, W., Peake, A.S., Poulton, P.L., McClelland, T., 2009. Re-inventing model-based decision support with Australian dryland farmers 4 Yield Prophet® helps farmers monitor and manage crops in a variable climate. Crop & Pasture Science 60, 1057–1070.
Hogarth, R.M., 2001. Educating Intuition. Univ. Chicago Press, Chicago.
Isenberg, D.J., 1986. The structure and process of understanding: implications for managerial action. In: Sims, H.P., Gioia, D.A. (Eds.), The Thinking Organisation: Dynamics of Organisational Social Cognition. Jossey Bass, San Francisco, pp. 238–262.
Jovchelovitch, S., Bauer, M.W., 2000. In: Bauer, M.W., Gaskell, G. (Eds.), Qualitative Researching with Text, Image, and Sound: A Practical Handbook. Sage, London.
Kahneman, D., Lovallo, D., 1993. Timid choices and bold forecasts: a cognitive perspective on risk taking. Management Science 39, 17–31.
Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. European Journal of Agronomy 18, 267–288.
McCown, R.L., 2005. New thinking about farmer decision makers. In: Hatfield, J.L. (Ed.), The Farmer's Decision: Balancing Economic Successful Agriculture Production with Environmental Quality. Soil and Water Conservation Society, Ankeny, Iowa, USA, pp. 11–44.
McCown, R.L., 2011. A cognitive systems framework to inform delivery of analytic support for farmers' intuitive management of seasonal climatic variability. Agricultural Systems 105, 7–20.
McCown, R.L., Carberry, P.S., Hochman, Z., Dalgliesh, N.P., Foale, M.A., 2009. Re-inventing model-based decision support with Australian dryland farmers. 1. Changing intervention concepts during 17 years of action research. Crop & Pasture Science 60, 1017–1030.
Meinke, H., Wright, W., Hayman, P., Stephens, D., 2003. Managing cropping systems in variable climates. In: Pratley, J. (Ed.), Principles of Field Crop Production, fourth ed. Oxford University Press, Oxford, UK, pp. 26–77.
Pearl, J., 2000. Causality: Models, Reasoning, and Inference. Cambridge Univ. Press, Cambridge, UK.
Potgieter, A.B., Everingham, Y.L., Hammer, G.L., 2003. On measuring quality of a probabilistic commodity forecast for a system that incorporates seasonal forecasts. International Journal of Climatology 23, 1195–1210.
Sharif, H.O., Yates, D., Roberts, R., Mueller, C., 2006. The use of an automated nowcasting system to forecast flash floods in an urban watershed. Journal of Hydrometeorology 7, 190–202.
Sloman, S., 2005. Causal Models: How People Think About the World and Its Alternatives. Oxford Univ. Press, Oxford.
Stone, R.C., Auliciems, A., 1992. SOI phase relationships with rainfall in Eastern Australia. International Journal of Climatology 12, 625–636.
Strevens, M., 1999. Objective probability as a guide to the world. Philosophical Studies 95, 243–275.
Strevens, M., 2006, Probability and chance. In: Borchert, D.M. (Ed), Encyclopedia of Philosophy, second ed. Macmillan Reference, USA.

Thagard, P., 2005. Mind: Introduction to Cognitive Science. MIT Press, Cambridge, Mass.
Vick, S.G., 2002. Degrees of Belief: Subjective Probability and Engineering Judgment. American Society of Civil Engineers Press, Reston, VA.
Woodruff, D.R., 1992. WHEATMAN: a decision support system for wheat management in subtropical Australia. Australian Journal of Agricultural Research 43, 1483–1499.