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Decision Support Systems in Agriculture: Some Successes and a Bright Future

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1. Introduction

This chapter is dedicated to the capture, preservation, reuse and learning of agricultural knowledge. We illustrate the potential of information technology with a simple example of a writing pen. Before the age of information, a person with a pen or pencil could write beautiful poetry. If she gave or loaned the pen to someone else, she could no longer write poetry, but the other person, would have gained a tool that helped write poetry. In this case, the first person's loss is the second person's gain, which, in economic terms, is a zero-sum game. Of importance is the fact that the relationship between the first and second person has changed and in order to continue writing poetry the first must obtain permission from the second to continue writing. Thus a certain measure of power has been passed with the possession of the pen and a dependency has changed between the first person and the second. Rare is the individual that does not see this as a clear disadvantage for the first person. Also rare is the relationship between two people that would not be strained by such a reversal.

Imagine, however, if the first person were to make a copy of the pen and give it to the second person, while retaining the use of the pen and thus suffer no loss in ability to write poetry. The relationship between the first person and the second changes from one of dependency to one of collaboration and mutual empowerment. Rare is the relationship between two persons that would not be strengthened rather than strained by the sharing of our information age pen. In this case no longer is it a zero-sum transaction. No longer is there the capable and the incapable. No longer is there gain of one at the loss of the other. Rather it has become a win-win situation in which all gain. Under these conditions, the first person is more likely and could be stimulated to make copies and distribute pens to everyone in the world, since it no longer results in their losing the tools to write poetry. This is the potential of information technology. Information technology can enable and empower us to share tools without the loss of use of the tool ourselves. It seems we have yet to fully exploit the potential of this technology.

2. Scope of this chapter

We will concentrate this chapter on agricultural knowledge, particularly that pertinent and relevant to tropical agroecosystems, largely because the bulk of our experience with decision-aids has been concerned with such production systems. Our thesis is that successful decision-aids need to recognize the inherent complexity of such systems. It is the thesis of this chapter that decision-aids can be tools to assist in the management of these

complex yet critical elements of human food security, partially through the capture of relevant knowledge and also through facilitating the accelerated learning/acquisition of the knowledge by others, and also through improvement in that knowledge as a result of the organization and representation effort.

This chapter will describe some of the authors' experience with decision-aids and their characteristics that have been useful in agriculture. The initial motivation to develop a decision-aid derived from the confluence of four conditions occurring at the onset of a newly formed, foreign technical assistance project in Indonesia (TropSoils, 1981):

1. The goal of the project was to provide improved soil and crop management for Transmigrants (farmers and producers from the "over-populated" rural areas of Java, Indonesia) in their new environment on Sumatra with relatively large amounts of land, but little land with the water needed for paddy rice cultivation, the system anticipated by government planners and desired by some farmers. The new homesteads in Sumatra provided little land suitable for paddy rice production. The more extensive land differed drastically from that on Java by being exceedingly acid, with pH values of 4.0 to 4.5 and high levels of plant toxic aluminum. Aluminum saturation values frequently exceeded 50%, indicating probable toxicity to food crop plants such as maize (*Zea mays*, L), peanut (*Arachis hypogea*, L.), and especially mung bean (*Vigna radiata*). Other soil constraints to food crop productivity included low levels of essential soil nutrients (phosphorus, potassium), which also were constraints rare in the rich Javanese soils. Thus the need was great to provide new ways for the Transmigrants to produce food and secure a livelihood in this strange, new environment.
2. Two US universities were tapped to provide the technical assistance (North Carolina State University, and the University of Hawai`i at Manoa). These universities had extensive experience dealing with soils taxonomically identical (Paleudults[1]) to those at the project site (Sitiung, West Sumatra). The immediate challenge was "How could the experience of producers and growers in the SouthEast US, Central and South America, which was largely experiential, but also recently scientific, be efficiently introduced and shared with the Transmigrants," who were in immediate need of food production technology on their new, but unfamiliar land.
3. A new perspective had just appeared in international agricultural development research circles, that of Farming Systems Research and Development (Shaner et al., 1982). The approach pointed out that farmers should be respected and very much involved in attempts to introduce new technology and practice. This approach also seemed to coalesce with Agroecosystems Analysis, as advocated by South East Asian scientists in the SUAN network (Rambo and Sajise, 1984).
4. Recent developments in information technology, specifically the new capabilities of software development efforts associated with Artificial Intelligence (Rich, 1983), were purported to permit medical diagnosis (Hayes-Roth et al., 1983). It was hypothesized at the time that the detection and possibly the prescription of soil and crop management solutions to the weathered, acid soils, would be analogous to the diagnosis and prescription of appropriate medication in similarly complex human health situations.

With this motivation the initial decision-aids were developed with the perhaps pompous title of "expert systems"(Yost et al., 1988).

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[1] Paleudults are soils of the Ultisol order, which are particularly old and highly weathered, associated with high, usually year-long rainfall. See Buol, S.W., F.D. Hole, and R.J. McCracken. 1989. Soil Genesis and Classification. 3rd ed. Iowa State University, Ames.

Because decision-aids are often developed to improve the capture, transfer (in a learning sense), and use of agricultural knowledge, the search for and development of successful decision-aids needs to begin with a thorough knowledge of agriculture. It might be yet more appropriate to search for the agricultural knowledge that is critical for providing food security and well-being. One of the hypotheses of the decision-aids effort described herein was that it was possible to capture, transfer (in a learning sense), and use this knowledge more directly---in contrast to simply writing chapters, books, and articles on the knowledge which must then be read and assimilated before the knowledge could be used.

3. Agricultural knowledge

Agricultural knowledge, that is the combined experience of how to grow and produce food, fiber, and bioproducts while securing a livelihood from the land, is extremely complex, comprised of multiple disciplines, multiple persons, with multiple levels of abstraction. Producer decisions range from considering the details of how a plant needs protection from pests and diseases, to planning commodity trading and marketing---all sometimes in a matter of minutes. Other producers' worries range from which variety of food crop to plant, to which field to plant first, to issues of food availability and alternative sources of income should food production fail. With such complexity, uncertainty, and variation over time, it is not surprising that agriculture as an enterprise is considered highly risky. White (personal communication, Cornell University, 2011) clusters the modern agricultural risks into 5 groups (1) Production risk, 2) Marketing/Price Risks, 3) Financial Risk, 4) Legal and Environmental Risk, 5) Human Resource Risks. Of those risks the primary one to be considered in this chapter is production risk. Production risk or productivity has been identified as an agroecosystem property by Conway (1986). He groups the major properties of agroecosystems thusly: 1) Productivity, 2) Stability, and 3) Resilience. Rambo and Sajise (1984) have expanded the number of properties to include those related to the human community associated with the agro-ecosystem (Table 1).

Property	Description
Productivity	The agroecosystem's output of goods and services.
Stability	The degree to which productivity remains constant.
Sustainability (now Resilience)	The ability of a system to maintain its productivity when subjected to stress and shock.
Equitability	A measure of how evenly the products of the agroecosystem are distributed among its human beneficiaries.
Autonomy	A measure of the extent to which a system's survival is dependent on other systems outside its control.
Solidarity	The ability of a social system (i.e. community) to make and implement decisions about collective behavior.
Diversity (Rambo, 1989)	Measure of the number of different kinds/types of components. Usually providing a greater range of options for change when necessary.
Adaptability (Rambo, 1989)	The ability of the system to respond to change in its environment to ensure continuing survival.

An example analysis of several agricultural systems from this perspective is given in (Yost et al., 1997).

Table 1. Agroecosystem properties. (Conway, 1987, Marten and Rambo, 1988).

4. Experiential knowledge

While the totality of agricultural knowledge is, as indicated above, exceedingly complex and diverse, we will consider a small subset of that knowledge in this chapter. We will focus on knowledge related to the growth and production of agricultural food crops and the role of nutrients, either in deficit or excess in that relationship. Agricultural knowledge is extremely descriptive with many adjectives and nouns, but few of the axioms, postulates, and theorems enjoyed by sciences such as physics and mathematics. Also as suggested above, agricultural knowledge tends to be encyclopedic with relatively few universal, nearly inviolable rules. In addition to exercising relatively few universal rules it is also clearly interdisciplinary, requiring close interaction among disciplines to adequately capture the experience.

Acknowledging the interdisciplinarity is important because the methods and norms of the various disciplines differ and should be respected in order to obtain the best knowledge from each of the disciplines. A personal experience illustrates differences among social and biological scientists, for example. Among biological scientists data almost always refers exclusively to numerical knowledge, weights of maize, metric tons of root crops, dollars per kilogram, kilograms of fertilizers or amendments, duration of crop cycles, while social science data can be notes taken during an intensive interview, during a focus group discussion, or as a result of a recollection. It is important in working with such diverse, interdisciplinary knowledge that disciplines are respected for their methods, techniques, approaches and culture.

4.1 Collecting and recording agricultural knowledge

Accurate collection and recording of agricultural knowledge, not surprisingly, must reflect the complexity of the knowledge itself. Such collection is difficult and success, not surprisingly, seems to require methods appropriate for the knowledge. Probably some of the best methods from the point of view of completeness are those used by anthropologists. Their holistic perspective requires unusually complete, thorough knowledge collection and recording using the most current methods available. One good example is the Ph.D. dissertation of Dr. Cynthia T. Fowler (Fowler, 1999), describing an agricultural community, Kodi, West Sumba, Indonesia. The dissertation required approximately 550 pages to record the relevant knowledge. A small portion of the dissertation was later synthesized into an explanation of an apparent oddity – that an introduced plant from another continent came to be a local 'sacred' plant (Fowler, 2005).

Another example of the capture of detailed agricultural knowledge is provided by the dissertation of Dr. M. Robotham (Robotham, 1998). Again, some 550 pages were needed to describe the agricultural system. In this case, Robotham attempted to generalize the knowledge and capture the decision-making logic from each of three villages located in the Philippines (ibid, 1998). Within each of the 3 sites, selected to represent variation in Philippine agriculture, multiple households were interviewed using social science techniques, with a total of some 17 households interviewed in all. Models of the apparent decision-making process were synthesized into decision-trees (graphs that represent the flow of decision-making, Appendix 1) to help compare and contrast the knowledge that had been developed for each of the villages.

Influences of socio-economic forces on agroforestry adoption in the Dominican Republic were modeled using a rule-based system (Robotham, 1996). Examples of a rule-based system will be forthcoming in section 5.2

Another effort, conducted by members of the TropSoil team of our study in Sumatra, Indonesia, was the attempt to capture the similarities and differences among the local people in contrast with the Transmigrants (Colfer et al., 1989). The results suggested that the rule-based knowledge representation structure was not ideal to capture and structure the information. It may have been that the knowledge was descriptive while the software was designed to capture decisions built on goals and rule-based logic.

5. Contributions of artificial intelligence to decision-aid development

(Rich, 1983) defines artificial intelligence (AI) as "the study of how to make computers do things at which, at the moment, people do better." She goes on to list various topics of interest ("problems") as of the time of her book that scientists in the field were working on:

- Knowledge representation
- Search strategies
- Reasoning methods
- Game playing
- Theorem proving
- General problem solving
- Perception (visual, speech)
- Natural language understanding
- Expert problem solving (Symbolic mathematics, Medical diagnosis, Chemical analysis, Engineering design)

Of particular interest to the authors of this chapter was the type of "Expert problem solving" of Medical diagnosis. This application of A.I. illustrates three contributions of A.I. to agricultural knowledge: *Knowledge representation*, *Search Strategies*, and *Reasoning Methods*.

5.1 Characteristics of experts

Glaser and Chi (1988) suggest that experts often display the following characteristics

- Excel mainly in their own domains
- Perceive large meaningful patterns in their domain
- Work quickly. They are faster than novices in performing the skills of their domain
- Have superior short term and long term memory
- See and represent a problem in their domain at a deeper (more principled) level than novices
- Spend a great deal of time analyzing a problem qualitatively
- Have strong self-monitoring skills

5.2 Knowledge representation

One of the first systems to carry out medical diagnosis was the software Mycin (Hayes-Roth et al., 1983) , which used a rule-based system to record and exercise expert knowledge. Rule-based systems were constructed from a sequence of "if then" statements illustrated as follows:

1. If Blood temperature is warm and method of reproduction is live

Then Animal = mammal

2. If Blood temperature is warm and method of reproduction is eggs

Then Animal = bird

The analogy seems obvious between diagnosing and solving a medical condition and that of diagnosing and solving a condition that is constraining or limiting a plant or food crop. This analogy was first recognized by several plant pathologists and resulted in the development of a system to detect soybean diseases (Michalski et al., 1981).
This structure was used in the first 'expert systems' developed by the authors. Rules used to capture the knowledge included, for example:
Rule 1: If the plant observed in the field is *Leucaena leucocephala,* L. and the plant is growing well then it is very unlikely that soil acidity would limit most food crop yields (80/100).
Rule 2: If the soil of the field is red and in a tropical environment then it is likely that soil acidity will limit food crop yields (60/100).
Rules 1 and 2 illustrate ways that observational information, i.e. the presence of a particular plant, can be recorded and can contribute to a conclusion that soil acidity may or may not be limiting. Rule-based systems were used to develop a wide range of diagnostic systems. In addition, these two rules illustrate a method not only to capture the logic in the if-then sequence, but also record some expression of uncertainty in the declaration of the logical relationship. In advanced rule-based systems combinations or rules with less than 100% confidence level would be combined to represent that uncertainty in the resulting conclusion. Some scientists developed methods of checking the consistency of combinations of various rules, by examining the veracity of the resulting conclusion.
Other methods of knowledge representation have been developed such as frames, semantic nets, but these are beyond the scope of this chapter. Given the complexity of agricultural knowledge, improvements in structures supporting knowledge representation continue to be needed. Specifically challenging are ways to combine qualitative and quantitative knowledge in ways that conserve both. Unfortunately, many combinations of these types of knowledge are possible only when the quantitative information is simplified to match the form of the qualitative and when the qualitative is expressed only in quantitative terms.

5.3 Search strategies

As indicated in Rich (1983) and other references, strategies for efficient search through huge networks, decision-trees and databases are needed. AI has provided some clear examples of search strategies such as a) Depth-first, b)Breadth-first, and 3)Best-first (Figure 1). A Depth-first strategy probes a knowledge-tree or a decision-tree by asking the detailed questions first in a limb of the tree (top downward) as the first path through the tree. A Breadth-first strategy, in contrast, searches all nodes at the same depth and then proceeds to the next lower level of nodes (or questions). The Best-first, however, is a combination of the best features of the Depth-first and the Breadth-first strategy. The Best features are those in which a heuristic[2], or specific knowledge, guides the search to choose at each node either a Depth-first or a Breadth-first strategy, depending on the knowledge. It's interesting to note that novices often choose a Depth-first strategy in probing a decision-tree and sometimes ask far too-detailed questions (deep into the decision-tree) too quickly, resulting in a failed search. In fact, this occurs so often that when someone exercises a Depth-first search, and it

[2] On a personal note, my Brazilian wife has shown me a very practical 'heuristic', she taught me how to cook rice by using the rule 1) add rice to the pan and 2) add only enough water to cover the rice by the depth of the distance between the tip of one's index finger and the first joint. Interestingly, some have speculated that this distance may coincide with the "inch" in English measurements. Less controversial is that this as an extremely convenient meter stick!

fails to find the correct answer, we tend to conclude that person is a novice! Experts frequently use the Best-first, where they may switch between search strategies based on their experience and awareness of the decision-tree content.

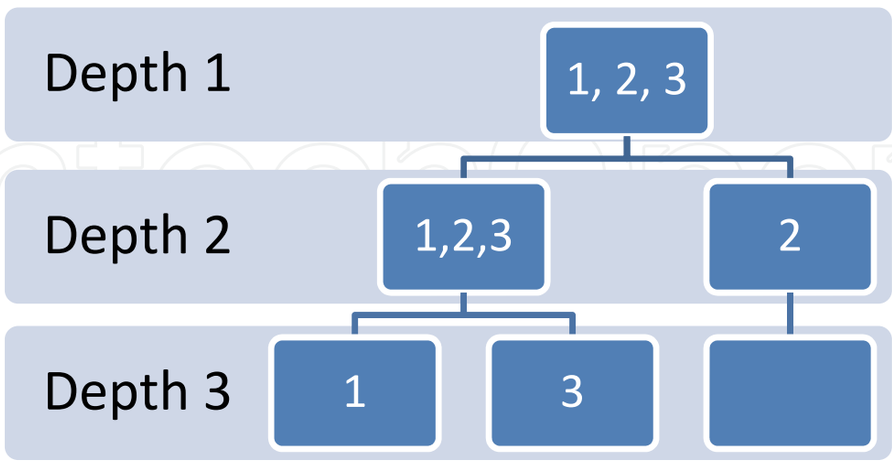

Fig. 1. Decision-tree illustrating Depth-first searches (pathway example 1), Breadth-first (follow pathway 2), and Best-first (follow pathway 3).

Recently, there has been renewed interest in search strategies that can exploit the rapidly expanding information base on the Internet (Watson-Jeopardy, 2011). These strategies may make qualitative information much more accessible to computer based reasoning systems.

5.4 Reasoning methods

A third contribution of AI to agricultural decision-aids (the first being *Knowledge representation*, the second is *Search Strategies*) is the choice between forward-chaining and backward chaining in terms of flow of the reasoning or inference through the decision-tree or set of rules. The forward-chaining method of reasoning begins with the observed facts and makes all possible inferences on the first pass through the decision-tree. The second and subsequent passes collect all facts originally observed plus all conclusions resulting from the first pass through the decision-tree. When the entire decision-tree is evaluated and all possible inferences are made the process is complete. The backward-chaining method begins with the same decision-tree but first evaluates the "goals" or final conclusions or inferences of the decision-tree, of which there typically only a few. Each of these "goals" is evaluated one at a time by determining what facts are needed for each of the goals to be concluded (succeed in being inferred). If any facts are missing that are needed for a specific goal, then that goal is discarded and the next unevaluated goal is similarly evaluated. Many of the initial expert system software programs chose backward-chaining as a reasoning strategy. The backward-chaining method of reasoning or progress through the decision-tree is often much more rapid than forward-chaining because major portions of the decision-tree are truncated if any rule does not have all of the necessary information and thus is evaluated as false. Readers interested in further details of these reasoning strategies are encouraged to consult recent texts or summaries on AI.

As this chapter is being written, new techniques of reasoning are illustrating that machines such as IBM's Watson can account for uncertainty in information and situations, by rank ordering multiple solutions to a given problem. The result is better performance than the best human players of the game Jeopardy (Watson-Jeopardy, 2011). This event is sure to be a

milestone in terms of managing complex and uncertain information, far exceeding the previous success of IBM's Deep Blue that excelled with the much more algorithmic game of chess. The success by Watson included the access of 15 terabytes of information accessed by 10 racks of IBM Power 750 servers, which generated 80 teraflops of processing power. Henshen (2011) reports that the 80 teraflops of processing power together with improved information access methods reduced information access time from 2 hours to 3 seconds.

6. Example decision-aids

Some of the authors used an expert system development tool (expert system shell) to implement a rule-based system that used backward-chaining to diagnose acid soil conditions and prepare predictions of the amount of agricultural limestone needed to remove the soil acidity limitation to selected crops. This software, ACID4, was described in (Yost et al., 1986) and subsequent decision-aids. We now present a list of various decision-aids developed and illustrate the range of uses, methods of implementation, purposes as well as unexpected benefits.

6.1 ACID4 rule-based system

6.1.1 Goal

Facilitate the transfer of the acid soil management knowledgebase developed in Southeast US, Central and South America to farmers and producers of the Transmigration area of Indonesia in general and Sumatra in particular.

6.1.2 Objectives

Implement a set of rules that together represent both the scientific knowledge and farmer experience in managing acid soils for food crop production. The primary source for the knowledge was a review paper by (Kamprath, 1984), practical experience reported by (Gonzalez-Erico et al., 1979), and firsthand experience by the authors.

6.1.3 Implementing language

EXSYS, expert system "shell"(Hunington, 1985.)

6.1.4 Successes

The ACID4 decision-aid illustrated that soil management knowledge could, indeed, be captured and represented in a computer-based decision-aid. The system permitted non-experts with only inputs of measured soil acidity (KCl-extractable acidity, calcium and magnesium and a selected crop) to receive predictions of lime requirements in tons of limestone per hectare (eq. 1).

$$\begin{aligned} &\text{Lime requirement}\left(\text{tons / hectare}\right) = \\ &1.4\left(\text{Exchangeable Acidity} - \text{CAS} * \text{ECEC}\right) / 100 \end{aligned} \tag{1}$$

- Where: Lime requirement is the amount of limestone of 100% $CaCO_3$ quality,
- Exchangeable Acidity is the KCl-extractable toxic aluminum and hydrogen,
- CAS is the Critical Aluminum Saturation, which is the maximum amount of toxic aluminum and hydrogen the specific crop can tolerate while achieving maximum yields.

- ECEC is the soil effective cation exchange capacity, which is the sum of the cations (Al, Ca, Mg, and K) as measured by a neutral salt.

The predictions of amount of limestone thus included current soil status of soil acidity, crop needs, quality of the limestone, and ancillary needs of calcium and magnesium in the soil.
An extensive comparison of ADSS, which was a slightly improved version of ACID4, indicated that the system made accurate predictions of lime requirements for maize (*Zea mays,* L.) and soybean (*Glycine max*, L.) but predictions for rice (*Oryza sativa,* L) and cassava (*Manihot esculenta*. L.) needed improvement (Dierolf et al., 1999).
Results from an exploratory, rule-based system FARMSYS (Colfer et al., 1989) illustrated that it was possible to merge multiple disciplines in a rule-based decision-aid. Ethnographic knowledge could be combined with knowledge of soil chemistry and management, when diagnosing and prescribing management when acid soil conditions were encountered. Local Minangkabau farmers preferred to grow rubber on their acid soils, which required no limestone applications and no tilling of the soil. Transmigrant Javanese and Sundanese farmers, on the other hand, would not hesitate to ameliorate their acid soils by applying the recommended limestone and tilling the soil for annual food crop production (Yost et al., 1992b).
Through repeated use of the decision-aid, users became familiar with typical requirements for particular crops, given usual levels of measured soil acidity, differences among soils and various crops. In fact, the users gained familiarity with the methodology, and learned certain aspects of the knowledge of managing acid soils. It is likely that some measure of the 'expert' knowledge was transferred to novice users through extensive use of the system. Perhaps the meta-level information was transferred to the decision-aid users as a result of using the system. It is clear, also that the detailed scientific knowledge was not transferred. Thus the mere use of the decision-aid does not replace the learning of the detailed algorithmic knowledge.

6.1.5 Observations

Further consideration of the factors affecting lime decisions indicated selection of lime materials could become impossibly complex. A linear programming model was developed that evaluated limestone cost, quality (fineness, neutralization capacity, as well as calcium and magnesium content), quantity available, and distance from the location for up to 5 limestone materials. These parameters were evaluated to provide a minimal cost choice of one or more of the limestone materials that met the specified soil pH and Ca and Mg targets in a spreadsheet decision-aid (Li et al., 1995).
While the main benefit of the decision-aid ACID4 was the use of the knowledge it contained, the process of organizing and recording the knowledge led to greater scrutiny of the knowledge and the identification of gaps and imprecision, which, in turn, led to improved subsequent research. This is illustrated in the evaluation of ADSS (a slight improvement over ACID4) (Dierolf et al., 1999). Thus, ironically, the preparing of the knowledge for dissemination, rather than detracting from the research process, actually improved and accelerated it. This meta-level analysis of the knowledge resulting from the crafting of the knowledge and representing it in the knowledge-base later proved to be extremely beneficial. This, in fact, may be a replication of the "patterns" and "larger framework" that experts seem to develop over time (Glaser and Chi, 1988)

6.1.6 Disadvantages

The ACID4 system provided a hands-on introduction to capture important knowledge and, for the Transmigrants of West Sumatra, critical knowledge about how to produce food on

these highly acid soils that differed so greatly from those of their experience. The system had several disadvantages including the following:

- The goal-driven, rule-based system proved rather unsuited to capture some of the information. In particular, social science information did not necessarily fit well in the rule-based knowledge representation system (Colfer et al., 1989).
- Many on-farm production limitations were due to multiple constraints occurring together. Acid soils in particular are characterized by multiple constraints. In addition to high acidity with toxic levels of aluminum and manganese. Levels of pH itself, calcium, magnesium, and phosphorus are to be expected to be insufficient and possibly yield limiting as well (Fox et al., 1985).
- A subsequent decision-aid was developed that attempted to address this problem (see section 6.4 NuMaSS, (Nutrient Management Decision Support System), later in this chapter).
- The system required a computer.
- This could be overcome by technicians and scientists running the software for the specific site or farm and communicating the results to the producer / grower.
- We later explore and propose a type of decision-aid that is completely graphic.
- Modification and updating of the software required rather expensive, proprietary software.
- One copy of the software could develop many systems (Le Istiqlal, 1986.)
- A small, free copy of the essential software was provided such that copies of the decision-aid could be copied and distributed inexpensively (run-time version).
- For subsequent decision-aids we used a procedure languages such as Pascal or declarative languages such as Prolog and hired programmers.
- Although the rules were given a numeric score of uncertainty, this uncertainty was combined in an inflexible way that often neither represented good practice nor the scientifically verifiable behavior.
- This effort led to subsequent improved representations of multiple sources of evidence (Bayesian cumulative probability) (Yost et al., 1999)---an implementation of evidence accumulation described in Pearl (1988).

Subsequent decision-aids included the cumulative probability to generate approximate confidence limits of numeric predictions of fertilizer needs using first order uncertainty analysis (Chen et al., 1997). This remains an area requiring more accurate representation of evidence accumulation as well as the appropriate handling of contradictory evidence. What are the most successful ways to carry out such calculations and accumulate evidence? It is likely that some of the methods recently used by IBM's Watson (Watson-Jeopardy, 201) would lead to better approaches than those described here. It also is not yet clear how successful experts make such estimates, if they do.

6.2 Propa (Papaya expert system)

That agricultural knowledge is highly interdisciplinary presents a challenge to the classical concept of an expert in a single discipline. When a grower or producer contacts the University with an issue they sometimes are referred to several experts before determining which expert is the right one for the specific problem. Confusion and failure to succeed in the diagnostic effort may occur. The goal of the Propa decision-aid was to explore this dynamic by attempting to construct a decision-aid that would identify and solve typical problems possibly requiring multiple disciplines (Itoga et al., 1990).

6.2.1 Goal
Develop an expert system comprised of multiple experts dealing with complex agricultural problems.

6.2.2 Objectives
Capture the knowledge of various scientists working with the papaya (*Carica papaya*) tropical fruit.

6.2.3 Implementing language
Prolog declarative language. Arity Prolog®.

6.2.4 Successes
The Propa decision-aid illustrated that it was possible for a group of experts from various disciplines to assess a case of a papaya problem and sort out which expert would be the primary expert to solve the problem. This was achieved through the use of a monitor and blackboard system that evaluated the interaction between the experts and the person with the papaya problem information. Each expert was assigned a dynamic relevancy factor which represented the success of their interaction with the papaya problem information. The disciplines brought together for the problem-solving session included experts in 1) Insect pests, 2) Nutrient management, 3) Disease identification, and 4) General management and good practice (Itoga et al., 1990).
Propa was able to show the user images of the various insects to assist and confirm their identification, which greatly assisted the insect expert's diagnosis and recommendation process.

6.2.5 Disadvantages
Test runs of the final system with users indicated that they were often overwhelmed with the number of technical questions that were asked of them by the group of experts. Many users were not prepared to answer dozens of questions about the detailed appearance of the plant and thus could not respond to the experts. When users could not respond to the expert's questions the experts were no longer able to proceed with a diagnosis.

6.3 PDSS (phosphorus decision support system)
The PDSS system development began in 1990 (Yost et al., 1992a).

6.3.1 Goal
Capture the knowledge, including both successful practice and the supporting scientific knowledge associated with the Diagnosis, Prediction, Economic Analysis, and Recommendations associated with managing nutrient phosphorus (P) in tropical food production systems.

6.3.2 Objectives
Capture a P management structure in a computer software decision-aid that would improve the management of the nutrient P.

6.3.3 Implementing language

Delphi® rapid application development software, Pascal language.

6.3.4 Successes

PDSS builds on the results of the structuring of the knowledge for the soil acidity decision-aid ACID4. As a result of the meta-analysis of the soil acidity decision-making process, we identified four components in the general process of nutrient management: 1)Diagnosis, 2) Prediction, 3) Economic Analysis and 4) Recommendation. These components served the basis for constructing PDSS and will now be discussed in succession.

6.3.5 Diagnosis

A diagnosis of a particular condition, in this case of a deficiency in soil and plant content of the nutrient phosphorus (P) is critical to bringing appropriate attention to the condition and, consequently, to its solution. A diagnosis in this sense can be observed when an expert is confronted by a problem and asks a few quick questions and rapidly determines the importance of further questioning or not. In this sense, the expert is exercising the "Best-First" search strategy discussed above. Such rapid assessments were observed when experienced scientists did field-visits, discussing with farmers the conditions of their crops. Often during such visits and discussions a suggestion resulted that led to corrective action. A diagnosis in this sense is our attempt to capture and implement an expert's best-first strategy of quickly assessing the seriousness of a situation and determining the best subsequent course of action. In another sense a diagnosis is a call to action. It is a decision about whether to act or not. This definition and use is important in terms of problem-solving and may be somewhat different than the classic "diagnosis" used in disease identification. The "diagnosis" we describe in this section is most effective if carried out by the person actually working with and intimately involved with managing the complex system (a crop-soil production system, in our case). A frequent heuristic or rule of thumb is that if a disease or condition is caught early then it is more likely to be successfully cured or remedied. Likewise, in complex systems of soil and crop management, a condition can often best be solved if it is detected early before subsequent, secondary complications, or in some cases irreversible damage, occurs. The analogy with human medicine is clear. For these reasons, it seems prudent for the grower, producer, or farmer to be informed and empowered with sufficient knowledge to detect the need for action. We also, upon further analysis, learned that there are other aspects of a good diagnosis that are important (Yost et al., 1999) (Table 1).

Diagnostic knowledge can be useful even if it is qualitative, highly observational, and even if a substantial amount of uncertainty is present. Highly uncertain information, when combined with other information with a similarly large amount of uncertainty, can, when taken together, begin to show a pattern that is typical of the disease, the condition or the state being detected. A good diagnosis could result from multiple pieces of information, none of which stands alone on its own, but when combined together, suggests a singular conclusion (i.e. all tending to indicate deficiency of a particular nutrient). We implemented this characteristic of being able to combine qualitative, quantitative, as well as uncertain information by using a Bayesian cumulative probability framework as indicated above in a chapter on Diagnosis (Yost et al., 1999). An example spreadsheet illustrating the calculations is shown in Appendix 2. The combining of multiple pieces of information thus often led to a

diagnosis when no individual piece of information was sufficient to provide a call for action. It was possible to include a consistency check, if mutually contradictory facts were observed. For example, if the probability of a nutrient deficiency for fact A was 0.9 that a P deficiency was likely (where 0 means certainty of no deficiency, 0.5 means complete ambivalence, and 1.0 means total certainty) and fact B had a probability of 0.2, then we have a situation of conflicting evidence. A rule was written to send a message to list in the output that a serious contradiction is occurring.

Table 1. Considerations in developing diagnostic questions. We suggest that the best diagnostic information/ tools/ questions are those that build on the common knowledge that on-site managers (e.g. farmers) have readily available together with simple measures, both qualitative and quantitative, of fundamental characteristics of the production system:

-The tool/question should be simple to use by lay persons.

-Results of the tool should be quick, such as the simple observation of a symptom or property in the field.

-Cost of the tool/question should be low or of no cost.

-The tool/question should be reliable as it should reliably indicate what action is to be taken.

Observations:

-Sometimes the result of the tool/question is that more expertise is required.

-Incomplete or imperfect data should not completely invalidate the diagnosis.

-The tool/question should take full advantage of the farmer, producer, or field observer's observation and knowledge.

-The tool/question may lead to improved, better diagnostic tools.

(Questions developed in a TPSS 650 Soil, Plant, Nutrient Interactions by students N. Osorio, X. Shuai, W. Widmore, R. Shirey. University of Hawai`i at Manoa)

We encountered two disadvantages of using the Bayesian accumulation of probability framework: 1) Much of our evidence and multiple observations or measurements were highly correlated or multicollinear. The multicollinearity contrasts with the assumed condition of independence in classic Bayesian evidence accumulation and thus the calculated cumulative conditional probabilities were in slight error depending on the degree of multicollinearity. 2) One could have strong evidence both for and against a condition as well as weak evidence for and against the condition, or even a complete lack of information, all of which would combine to a value of 0.5. As a result, strong, but conflicting, evidence is wholly discounted. One of our inadequate solutions to this situation was to monitor evidence and when evidence for and against a particular outcome differed substantially, a message was attached to the conclusion warning of the information conflict.

6.3.6 Predictions

The Prediction in PDSS is usually a numerical amount of a specified amendment needed to resolve the nutrient deficient condition identified in the Diagnostic section. There may be additional inferences based on the additional data usually required to complete the numerical prediction. There is a possibility that, upon analysis of the additional information, a prediction of no requirement may occur. The Prediction was developed using a combination of both scientific and local experiential knowledge. The preferred knowledge is that occurring when the best scientific methodology is gleaned from the literature and tested in the unique local soil, crop, weather, economic, and social conditions. To obtain and ensure such knowledge clearly requires intense work by the local scientists as well as the knowledge engineer (the person who organizes the knowledge and structures it into the knowledge representation format of the decision-aid software). In our case, scientists have included both international experts as well as local agricultural scientists who were in the process of or had completed field studies of the prediction methodology.

The choice of which knowledge and how much detail needed to be recorded and represented in order to minimize excessive detail and yet retain the essential knowledge was and seems to be a challenging one. This aspect has been lucidly discussed in Stirzaker et al. (2010). As Stirzaker et al. (2010) indicate, the typically detailed information resulting from research, needs to be smoothed and simplified to be most effectively used in a working system. Our experience has been identical and this aspect of building decision-aids seems to us to be one that requires close interaction and discussion with the intended users to best ascertain the appropriate level of detail. Thus it is clear that the direct transfer of algorithms and conclusions from a research effort is seldom possible without the requisite simplification described by Stirzaker et al. (2010). The intense and repeated contact between the developer and the client or user group has been essential in our experience. This type of intense interaction has come to be termed "extreme programming"(Beck, 1998; Wells, 2001). This programming style is based on frequent viewing and discussing of the software being developed with representative, intended users.

One of the requirements of the Prediction step that is necessary for the integration with the subsequent components is that there be a numeric prediction. This numerical value forms the basis of the benefit/cost analyses carried out in the subsequent Economic Analysis section. The Prediction equation of the PDSS decision-aid is thus an equation that began with the rather simple description given in (Yost et al., 1992a) shown in equation (2).

$$\text{P requirement} = \left(\text{Soil P required} - \text{Soil P present}\right) / \text{Reactivity of the soil to added P} \tag{2}$$

Where: P requirement is the kg/ha of fertilizer P needed to increase the soil P level ("Soil P present") to match the "Soil P required" and thus meet the specific crop's requirement for nutrient P. While equation (2) gives the basic structure of the P requirement prediction equation, there were updates to the equation which gradually increased in detail and complexity (eq (3)).

$$\text{P requirement} = \left(\left(\text{PCL} - \text{Po}\right) / \text{PBC} + 0.8 * \text{PBC} * \text{Puptake} * 0.8 * 1 / 2\right) * \text{Placement factor} * \text{Application Depth} / 10 \tag{3}$$

Where:

PCL = P critical level of the crop using a specific extractants ("Soil P required"of eq. 3)
Po = Initial, measured soil level of P using an specific extractant ("Soil P present" of eq. 3)
PBC = Phosphorus Buffer Coefficient using a specific extractant ("Reactivity of the soil to added P" of eq. 3)
Puptake = Yield of crop component removed*P content of the removed tissue (not present in eq. 3)
Application depth = Depth to which the fertilizer is incorporated (not present in eq. 3)
Placement factor = A factor that represents the relative efficiency of localized placement in reducing the P fertilizer requirement (not present in eq. 3)
The predictions developed in PDSS, as in ACID4, also included an expression of the associated uncertainty. In the ACID4 and FARMSYS modules the uncertainties were personal estimates of the reliability of the rules being exercised. In PDSS a different approach was used, that of error propagation (Burges and Lettenmaier, 1975). The error propagation calculation resulted in a very useful assessment of the equation's prediction. This was later expressed as the confidence limits of the prediction. An example of a prediction of P requirement was carried out on an experiment done at the Centro Internacional de Agricultura Tropical (CIAT) in Cali, Colombia and is illustrated in Figure 2. An interesting result of this prediction was that the actual precision of the fertilizer prediction was approximately +/- 50% of the requirement in most cases. This large error pointed out the typically large uncertainty in fertilizer predictions. One advantage of the first order uncertainty prediction was the ranking of sources of variability in the prediction equation. This enabled prioritizing research effort to better understand and make predictions (Chen et al., 1997).

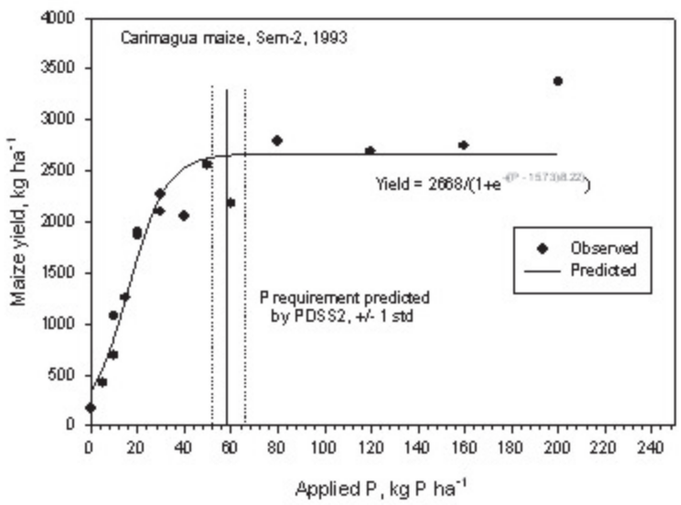

Fig. 2. Comparison of PDSS prediction with field estimates of the amount of fertilizer phosphorus needed to achieve maximum yield (CIAT, 1993)

6.3.7 Economic analysis

Economic analysis was the third component. This component clearly differed from the other portions of the decision making process requiring an economic calculation of profitability resulting from resolving the Diagnosed problem using the Prediction methodology. As

indicated above the construction of this component required quantitative output from the Prediction component in order to carry out the calculation of the benefit resulting from the solution of the diagnosed problem. This, for example, required a quantitative estimate of the amount by which the crop yield was increased as a result of supplying the necessary nutrient phosphorus. Understandably this required more than the usual soil science solution to increase extractable P. In PDSS, this required an estimate of crop growth response, which required estimating crop behavior at various levels of extractable soil P. This requirement meant that we had to incorporate plant response in addition to the simple chemical evaluation of extractable P. Thus we had to fill yet another knowledge gap in order to link the Prediction module with the Economic Analysis module. We found this "stretch" to ensure module communication helpful and broadening. As a result we gained an improved perspective of the decision-making process. The ultimate advantage was that we could conduct sensitivity analysis of the effects of change in extractable soil P on crop yield, profitability, and benefit/cost.

The adopted methodology for economic analysis was a simple partial budget analysis. This type of analysis permitted a quantitative calculation of benefit versus cost, giving some indication of economic advantage of the practice suggested in the Prediction step. The strength of the partial budget assessment was the minimal data requirement. The weakness, of course, was that the entire enterprise could be losing money but if the addition of fertilizer was resulting in yield increases considering fertilizer costs, the analysis would report a profit. Another weakness, from an anthropological point of view is that economic analyses capture only part of people's decisionmaking logic----issues like gender/ethnic division of labour and circular migration issues, symbolic meanings of particular crops, distaste for handling of fertilizers, food crop taste preferences, etc. are ignored...[of varying relevance, depending on local conditions]. In addition, the partial budget assumes no interactions among the fertilizer variables with other factors in the enterprise. Since the exploration of the consequences of various cost and benefit scenarios is often helpful for decision-support, a separate form was constructed to facilitate entry and calculation of benefit/cost given various price inputs.

6.3.8 Recommendation

The fourth and last component of the structure of nutrient management revealed as a result of the meta-level analysis of the decision-making process was the Recommendation. The Recommendation as identified in this analysis is the process and result of summarizing the entire decision-making process and includes the Diagnosis, Prediction, and Economic Analysis, and presents this information in a way that the decision-aids user can utilize. Understandably this varies with the needs, knowledge preferences and capabilities of the users. In the case of PDSS software a simple page is constructed that includes the specific segments of Diagnosis, Prediction, and Economic Analysis, and concludes with a list of the warnings (aspects of the consultation that could be seriously in error) or information notes that supplement the conclusions of the consultation.

The Recommendation, in the case of the SimCorn decision-aid (a decision-aid developed by scientists at Kasetsart University using the knowledge and algorithm implemented in PDSS) for the diagnosis, prediction, and economic analysis of fertilizer quantities for maize, was a book of recommendations that could be used by local extension officers to interpret soil test results and to communicate specific amounts of fertilizer blends for producers and growers in their region. In this case, the extension officers provided the information verbally rather

than distributing leaflets and tables of fertilizer recommendations (Attanandana et al., 2007; Attanandana, 2004; Attanandana and Yost, 2003; Attanandana et al., 2007).
Preparing the decision-aid knowledge for the Recommendation thus requires close contact and familiarity with the clients, or with the agents who will be the direct users of the software. As discussed in Attanandana et al. (2008), the results of the decision-aid consultation should be prepared in a form that enables and empowers the producer/farmer who will be using the results. The preparation of the Recommendation thus completes the process of close contact with the eventual user of the decision-aid results that we consider essential for the crafting and construction of the decision-aid as well as its application (Attanandana et al., 2007; Attanandana et al., 2006).

6.3.9 Reaction to the PDSS decision-aid among differing collaborators

The PDSS system and the knowledge contained therein was found useful in various ways by our collaborators. For example, our Thai colleagues sought to include PDSS for the P algorithm contained therein. They incorporated the logic and equation into their own systems, SimCorn and SimRice (Attanandana et al., 2006). Our colleagues in the Philippines, however, preferred to receive the PDSS algorithms in the form of the more integrated NuMaSS software, to be discussed subsequently, which combined the nitrogen, phosphorus, and soil acidity components (Osmond et al., 2000).
The use of the PDSS algorithms in our collaborators' software SimCorn (Attanandana et al., 2006) reduced the recommended application of phosphorus by roughly 50% (Attanandana, 2003, personal communication) reducing the requirement for foreign exchange to purchase fertilizer P, and limiting the accumulation of environmentally harmful levels of nutrient P.

6.3.10 Expansion and extension of the PDSS decision-aid

The PDSS decision-aid, first released in 2003, proved to be a decision-aid in development. The development of PDSS, similar to the development of ACID4, opened up new possibilities and suggested several additions and generated multiple research activities. The areas where additional knowledge was prioritized included the addition of a potassium module especially for work in Thailand. Also in Thailand and in West Africa, we needed to help identify rock phosphate-favorable conditions as well as the amounts that should be applied to alleviate P deficient conditions. And, lastly, we needed to diagnose and predict nutrient requirements in perennial cropping systems such as trees, which was clear from the intial work with decision-aid ACID4 in Sumatra, Indonesia.

6.3.11 Improving predictions of the PDSS

As a result of calculating the error in the prediction (Chen et al., 1997), which gave confidence limits on the decision-aid prediction, we also obtained the relative ranking of error in each of the input variables. This information was then used to identify the greatest source of error in the prediction. This led to the identification of follow-up research designed to reduce error and uncertainty in the predictions. Follow-up work was carried out, for example, to better estimate and predict the buffer coefficient for phosphorus in various project sites (George et al., 2000).

6.3.12 Potassium module

Another substantial gap in the nutrient management of crops for food and fuel in the Tropics included the need to assess the potassium (K) status of highly weathered soils. We

expect deficiencies in potassium to occur and indeed our experience has been exactly that in Thailand (Attanandana and Yost, 2003). With assistance from our collaborating institution and local research support, a study of methods for diagnosing and predicting potassium requirements was completed. Based on this result and when integrated with other preliminary research, a tentative potassium prediction model was proposed (Yost and Attanandana, 2006), eq. 4.

$$\begin{aligned} &\text{K requirement } \left(\text{kg K ha}^{-1}\right) = \left(\text{Kcritical} - \text{Ksoil}\right) / \text{BCK x B.D. x} \\ &\left(\text{Application depth} / 10\right) \text{x Placement factor} + \\ &\left(\text{Biomass removed x K content in the biomass}\right) \end{aligned} \tag{4}$$

Where
K requirement = the amount of fertilizer K that is needed to restore the soil K supply such that crop yields were maximum
Kcritical = The level of soil K needed to ensure that maximum growth and productivity occurred
Ksoil = The measured level of soil K
BCK = The soil buffer coefficient, i.e. the reactivity of the soil to added K, using the same extractant as Ksoil
B.D. = Soil bulk density (specific gravity), i.e. the weight of soil per unit volume
Application depth = The intended depth of incorporation of the fertilizer K in cm
Placement factor = A fraction that represents the relative benefit from application to a fraction of the soil volume at the specified depth to be fertilized
Biomass removed = The amount of crop bioproduct that is expected to be regularly removed from the field
K content of the biomass = The K content of the portions of the crop that will be removed from the field
Subsequent comparisons of yield and profit from farmer practice as compared with decision-aid recommendations indicated yield increases where K was applied according to predictions and increases in profit (Attanandana et al., 2008). Further and more detailed studies indicated that new methods for K diagnosis should be considered (Nilawonk et al., 2008).

6.3.13 Rock phosphate module

Another substantial gap in the nutrient management of crops for food and fuel in the Tropics included the need to consider locally available sources of nutrient phosphorus. This was an issue both in Thailand and in Mali, West Africa. A systematic analysis of the issues and factors that control rock phosphate effectiveness was carried out and the results were organized into a decision-tree and logical sequence (Sidibé et al., 2004). This author proposed a comprehensive approach to determining whether and how much of a specified rock phosphate material should be applied to restore crop productivity. The result was an algorithm that successfully predicted rock phosphate applications in acid sulfate soils of Thailand (Yampracha et al., 2005).

6.3.14 Perennial crops module

Initially, the project anthropologist observed that local communities had long preferred perennial crops for a variety of reasons later to become apparent (Colfer, 1991; Colfer et al., 1989).

Subsequently, it was apparent that in some high rainfall tropical environments the repeated clearing of land for food crops resulted in exposing bare soil to the intense rainfall. This could result in damage to the soil status either by leaching and loss of soluble nutrients on one hand (Dierolf et al., 1997), loss of enriched, surface soil through soil erosion, or both. In certain environments a more conservation-effective agro-ecosystem may be a perennial production system that provides regular food production but where the soil surface remains covered and protected from the typically highly erosive rainfall of humid tropical environments, such as those of tropical Indonesia.

A meta-level analysis of nutrient management structure and options in perennial cropping systems suggested that there also was a discernable and distinctive structure in perennial cropping systems and that the structure included the following: 1) A nursery phase, in which the seeds of the perennial plant were germinated and young plants begun, 2) An establishment phase in which the small seedlings were outplanted into the land that would become a forest, 3) A period of fast growth, and 4) A mature phase, in which production continued for many years (Figure 3). A review of the literature was assembled considering the perennial producer peach palm (*Bactris gasipaes*, L.) (Deenik et al., 2000).

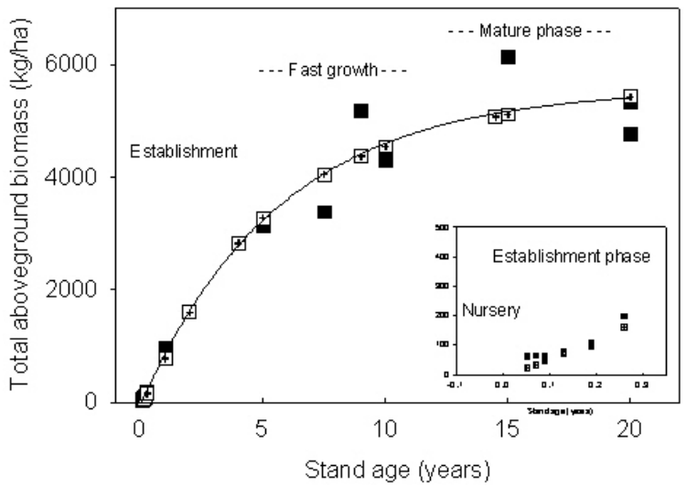

Fig. 3. A graphic depiction of four stages of particular importance in the management of nutrients in perennial crops (Deenik et al., 2000).

As in the case of other meta-level analyses of the agricultural systems, numerous gaps were observed in the available nutrient management in perennial crops when viewed from this perspective. As a result several studies were undertaken including collaborators, especially of the University of Costa Rica and the EMBRAPA/Amazon center in Brazil (Ares et al., 2002a; Ares et al., 2002b; Ares et al., 2003; Yost and Ares, 2007).

6.3.15 Summary

The meta-level assessment of patterns and structure, found so helpful in the development of ACID4, was quite helpful in the course of developing PDSS. The meta-level analysis of the knowledge base resulted in numerous improvements in the concepts and content of nutrient management in the body of knowledge (knowledge-base) surrounding the nutrient phosphorus in tropical ecosystems. The identified structure (Diagnosis, Prediction,

Economic Analysis, and Recommendation) identifies major components in the decision-making process and helps the user step through the process.
Developing a tool that predicts actual quantities of fertilizer needed given specified data illustrates that multiple disciplines can contribute to solutions in a systematic, synergistic way provided a common language is used. Is it true that computer-based knowledge systems can better accommodate and use multiple disciplines than humans?
A structure was proposed that enabled a monitor to guide and organize a multidisciplinary search to solve an unidentified problem in papaya problem diagnosis.
The calculation of propagated error in the prediction of fertilizer quantity at approximately 50% illustrates that despite attempts to achieve highly precise estimates in agronomic research, the results need improvement to better support economic and environmental objectives. The calculation of propagated error identified the variables most contributing to error. These variables became objectives for research to improve prediction accuracy and precision.
Conducting research to produce a knowledge module provided a clear, stimulating objective and resulted in high quality, problem-driven, and yet rewarding research.
The meta-analysis of the decision-making process and surveys of the users resulted in the identification of knowledge gaps that, in turn, resulted in numerous educational opportunities for young scientists. They conducted their research knowing that the results of their work would fill a gap in a working knowledge-base. The following scientists completed dissertations and Ph.D. degrees during this work (Gill, 1988; Evensen 1989; Agus 1997); Deenik, 2000; Diarra et al., 2004; Dierolf et al., 1999; Nilawonk et al., 2008; Sipaseuth et al., 2007; Yampracha et al., 2005).

6.4 NuMaSS (nutrient management support system)

The NuMaSS Project was designed to join the individually developed decision-aids ADSS and PDSS, with a new system to be adapted from a nitrogen decision-aid (Osmond et al., 2000).

6.4.1 Goal

The NuMaSS Project was developed to integrate and disseminate decision-aid tools that diagnose soil nutrient constraints and select appropriate management practices for location-specific conditions. The strategy was to develop globally applicable, largely computer-assisted, integrated decision-aids that could both diagnose and prescribe appropriate solutions to soil nutrient constraints.

6.4.2 Objectives

The Project had three objectives 1) Improve the diagnosis and recommendations for soil acidity and nutrient problems. 2) Develop an integrated computerized knowledge-base, and 3) Develop auxiliary tools resulting from the integrated knowledge-base to assist producers to diagnose and solve soil acidity and nutrient constraints.

6.4.3 Implementing language

The rapid application development package Delphi®, which was a Pascal-based development environment.

6.4.4 Successes

The integrated software was comprised of existing modules of PDSS and ADSS, both modified to merge into the integrated framework called NuMaSS (Nutrient Management Support System). A nitrogen module was added by North Carolina State University based on the Stanford (1973) approach of determining a balance of what the crop needed relative to the soil content with amendments and fertilizers added. The actual implementation, while based on the Stanford approach, grew out of a dissertation of one of the project members (Osmond, 1991). The NuMaSS software was disseminated in countries in West Africa, Central and South America and in S.E. Asia (Thailand and the Philippines).

One of the notable initial successes of NuMaSS was that by following the diagnosis of soil acidity conditions and following with the proper soil amendments, desired crops such as mung bean (*Vigna radiata,* L.) could be grown where the crop had died previously due to the high soil acidity (Aragon et al., 2002). The decision-aid also indicated that other crops could be grown and would require substantially less expensive limestone than did mung bean. The initial success continued and gradually attitudes and awareness towards soil acidity changed and producers became aware of the importance and limits in productivity it caused. Several assessments of farmer attitude indicated substantial change in awareness and prioritization of soil acidity (Aragon et al., 2002). An impact analysis at the conclusion of the project reported that during the next 40 years the project results were conservatively estimated to return about 45 million $US in benefits to the producers (Walker et al., 2009).

Some other spectacular results occurred on the island of Negros Occidental where farmers and producers had not been applying limestone and were basically unaware of soil acidity. In this province maize yields of over 7 metric tons were obtained with the addition of nutrients according to NuMaSS predictions. This contrasted to yields of maize of 1 to 2 tons without the addition of nutrients or limestone (D. Cidro, 2006 personal communication).

The impact of the introduction of NuMaSS and introducing specific management of the acid, uplands soils seems on track to expand and extend well beyond the province of Isabela where the Walker et al. (2009) study took place. Other provinces of Northeastern Luzon have begun instituting province-wide programs of applying limestone. This contrasts to the total lack of commercial agricultural limestone in the regional city of Ilagan when the project begun. It was not clear that the rapid and extensive adoption of the liming technology was due to NuMaSS, but it seems likely that the dissemination was enhanced by the presence of the decision-aid.

6.4.5 Disadvantages

While it is clear that the NuMaSS software assisted and improved food crop yields in the Philippines, it was also clear that there were problems with the nitrogen component, especially in Thailand and Laos. A dissertation study was carried out comparing N recommendations from two decision-aids (NuMaSS and DSSAT (Jones, 1998)). The results indicated that neither software adequately estimated the minimum amounts of fertilizer N that should be applied. A dissertation study indicated that there was substantial residual nitrate that should be measured and which reduced the fertilizer nitrogen requirement (Sipaseuth et al., 2007).

Unfortunately, the results of the multiple expert work described in the Propa system (see section 6.2) had not yet become available and separate, non-interacting systems for nitrogen,

phosphorus, and acidity were constructed. In addition time did not permit the full integration of the potassium, rock phosphate, and perennial crop modules that had been developed for PDSS, to be integrated into the NuMaSS system.

6.5 NuMaSS-PDA (nutrient management support system for personal digital assistants)

Scientists at Kasetsart University, Bangkok, Thailand were among the first to attempt to diagnose and make fertilizer recommendations at the field-level using decision-aids (Attanandana et al., 1999). These scientists adapted simulation model output for use by local growers / producers in their efforts to apply site-specific nutrient management on their land (Attanandana and Yost, 2003). This approach was an attempt to adapt the concepts of Precision Agriculture, which broadly seeks to apply the right amount of the right nutrient at the right place at the right time, to the small farms of the Tropics (Attanandana et al., 2007). This included invention and use of the soil test kit, identification of the soils in the field using simple field observations (Boonsompopphan et al., 2009) and simplification of complicated simulation models (Attanandana et al., 2006; Attanandana et al., 1999) so that fertilizer recommendations could be made in the field. These efforts led to the assembly of the SimCorn, SimRice, and subsequently to the SimCane software (Attanandana et al., 2006). The NuMaSS-PDA was an attempt to harness the new capability of handheld computers and smartphones to provide the decision-support for the process.

6.5.1 Goal

Re-structure and re-organize a subset of the knowledge in the NuMaSS software for delivery on a hand-held computer so that one could go to a producer's field, sample and analyze the soil, identify the pertinent soil series, and conduct the diagnosis, prediction, economic analysis, and prepare a recommendation on site.

6.5.2 Objectives

Adapt essential parts of the NuMaSS decision-aid for delivery on a handheld device. Add the potassium decision-aid module to that of the nitrogen and phosphorus, thus providing direct support for the typical N, P, K fertilizer decision-making. Develop a simple method so that interaction and use of the decision-aid would be possible in multiple languages with simple addition of a simple dictionary for each language.

6.5.3 Implementing language

Superwaba®, a Java-based language. Palm OS, Windows Mobile OS.

6.5.4 Successes

A multilingual interface was developed that would permit interaction with users from a large number of languages. The nitrogen, phosphorus, potassium and liming modules were joined and executed properly in the SuperWaba environment. The initial languages implemented included English, French, Portuguese (Li et al., 2006). Subsequently, Tagalog and Tetun were added. Development concluded as the project drew to a close.

6.6 Visual decision-aid

In numerous regions of the Tropics access to a computer, an agricultural officer, or highly knowledgeable producers / growers is difficult or impossible. In other cases, even access to

written literature does not provide access to the knowledge written there. Nevertheless, producers and growers are intensely aware of, and clearly survive on visual information. We began an attempt to explore the possibility of stimulating awareness and transfer of information, or learning by a completely visual approach. This was a completely visual guide to the installation of a water conservation technology called "Amenagement en courbes de niveau" (ACN) in West Africa. This water conservation technique was developed by CIRAD (Gigou, 2006) and later characterized (Kablan et al., 2008). Adoption of the technology was slow, in part, due to the requirement for expert delineation of the contours in the field. Demand for the technology far out-stripped the availability of the local scientific staff. Professional staff are required to survey the hydrological issues in the field and devise strategies to handle the issues and locate the contours. The visual aid, Visual ACN, illustrated in Appendix 3, is proposed to illustrate, inform, and instruct in the installation and maintenance of the technology including the illiterate, which often may be women farmers, for example. The decision-aid in this case was not a computer software; rather it was a simple guide based on a sequence of two figures or drawings per page illustrating the condition and the solution on each page. We have conducted test distributions of the guide, which have stimulated substantial interest among local producers and growers (Figure 4).

Fig. 4. Long time, successful ACN (Amenagement en Courbes de Niveau) user, M. Zan Diarra, Siguidolo, Mali, West Africa examines the Visual ACN decision-aid with interest (photo: R.Kablan). How to assess what he might be remembering or learning from the visual information?

6.7 Decision-aids to assist learning / education

Use of the decision-aids was found to stimulate and enable learning in several ways.

- Operating the decision-aid by entering the requisite data. Carrying out the calculations and recording or transmitting the results helped users gain familiarity with the software and elements of the decision-making process. Merely operating the software did not result in the users gaining the knowledge embedded in the software, but to the curious it led to questions and sometimes sparked curiosity.
- Observant users gained some measure of the types of information needed and could test the system integrity by checking test cases. A feature of the early expert system shells was back-tracking that demonstrated the logic that led to a specific conclusion. With later decision-aids this feature was not present so supplementary information surrounding the consultation had to be selected and specifically added at the Recommendation stage.
- The rigor imposed by the decision-aid on the user, i.e. having to provide an answer in every run or consultation, reinforced and reminded the users of the need to have information from a specified group of interdisciplinary knowledge bases. The input from farmers as local experts, both improved the system and provided positive feedback to them.
- For some users the rigor of having to answer, in a precise way, was difficult and resulted in loss of interest and failure to complete the consultation.
- Use of a decision-aid can illustrate to users the need for and value of interdisciplinarity.
- Exposure to the way knowledge can be organized provides an exposure to a meta-level appreciation of the problem-solving techniques, which can support learning.
- The structure of the decision-making process illustrates one type of problem-solving that users can adopt or modify for themselves in the future as needed.

6.8 Summary

This chapter illustrates that complex agricultural knowledge could be captured and implemented so that numerical predictions and informed recommendations could be produced. In the example given, soil and crop management technology and knowledge on acid soils was captured from successful practice in the Southeast US, Central and South America and implemented in analogous soils in Indonesia.

Use of the decision-aid by users in a new location where soil acidity or phosphorus was limiting helped users identify data needs for solving such problems. For example, improved management of acid soils acid soils in the uplands of the Philippines was stimulated by the introduction of the decision-aid NuMaSS. The improved management included introducing the practice of liming. As a result producers and growers in the region were expected to benefit over 45 million $US, according to the impact analysis conducted in 2007.

The knowledge engineering process led to a meta-analysis of the process, i.e. some thought about how to best solve nutrient management problems. The result of the meta-analysis was the identification of a structure in nutrient management decision-making. A structure of Diagnosis, Prediction, Economic Analysis, Recommendation was proposed. This structure guided the formulation of PDSS, NuMaSS, and NuMaSS-PDA.

6.9 Challenges

Improved knowledge structures are needed that better match the nature of the knowledge.

Improved methods of knowledge representation are also needed such that the knowledge does not die when a software falls out of use or is discontinued. The use of pseudo-code or alternative knowledge capture may be an useful in this regard.
The knowledge engineering process is expensive and time consuming. The knowledge capture process needs further streamlining so that non-experts can record and exercise their knowledge.
Better software tools are needed to enable decision-aids to serve the learning / teaching function.

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6.11 Abstract

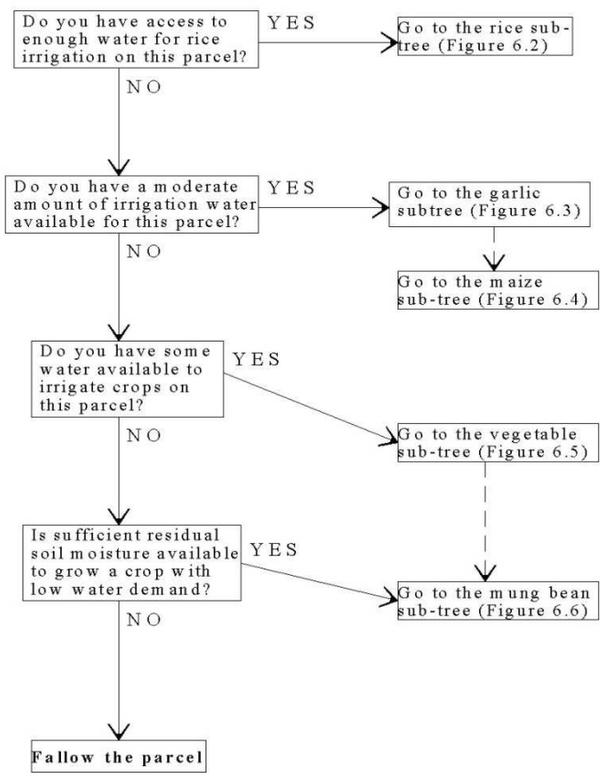
The application of Information Technology to agricultural knowledge in the form of decision-support systems and decision-aids has already been successful and offers great promise of more success in the future. This chapter will discuss the complex characteristics of agricultural information and the challenges it presents to society and to Information Technology (IT) to capture, organize, and disseminate this knowledge. Successes resulting from the application of IT to agricultural knowledge are discussed. The challenging characteristics of agricultural knowledge are that it is 1) Highly experiential and highly situational, 2) Characterized by outcomes and results that are risky, uncertain, with many events minimally predictable, 3) Interdisciplinary in nature, ranging from social sciences to biology, chemistry, physics, and mathematics. That this knowledge has been an extraordinary challenge for IT to capture is well-known and it is not surprising that new methods, structures, and systems continue to be required to capture the information.

Agricultural knowledge remains in a much earlier more descriptive stage of development, where personal observation and personal experience play a primary role in understanding agriculture and attempts to control or manage it. It is the thesis of this chapter that information technology can play a role in moving agriculture along to a more advanced stage of development by recognizing consistent trends, patterns, rules of the trade, rules of thumb and building upon such knowledge. Meta-analysis of the state of agricultural knowledge should be encouraged as being helpful to the process. The understanding of the causes of risk and uncertainty is relatively recent as are the benefits from systems studies conducted at a relatively high level of abstraction. Some examples include the identification of "tipping points" and their recognition in fragile ecosystems. Other aspects of the mathematics of catastrophe theory seem to offer benefits of perspective and overview of complex systems such as agriculture. The highly interdisciplinary nature of the knowledge, while involving virtually the full range of human knowledge systems, goes well beyond the scope of traditional biological, physical, and chemical disciplines. Of particular note is the importance of social sciences in the understanding and in attempts to control and manage real agricultural systems. As indicated, the need for decision-support systems to consider the human element in observing, capturing, and delivering management expertise is well known and several examples have been given. Preliminary exploratory decision-aids are discussed and the results of the development effort are chronicled in this chapter. One example depicts the capture for knowledge associated with the management of acid soils, developed in the SE US, Central America, and South America, and enable its transfer and

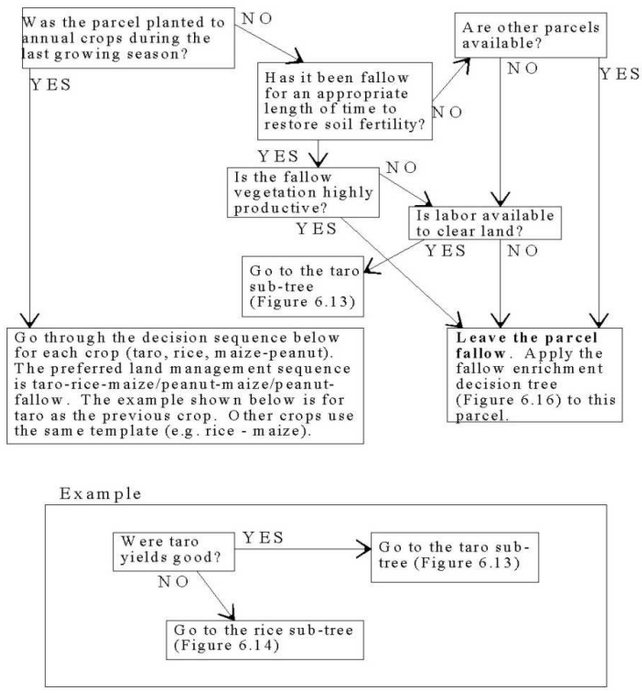
adaptation by farmers of upland cropping systems in the province of Isabela, The Philippines. There acid soils abound but techniques of acid soil management were not to be found. The results of the capture of both the experiential and scientific knowledge led to the identification of patterns and structures in the knowledge. Four components of nutrient management decision-making were identified and proved to be helpful in understanding, predicting, and controlling the management of nutrients in tropical soils. These included the Diagnosis, Prediction, Economic Analysis, and Recommendation components of nutrient management decision-making. Numerous gaps in both knowledge representation, knowledge organization, and in the use of decision-aids to support and transform teaching and learning remain. Nonetheless, it seems the potential of information technology is yet to be understood and certainly not realized.

7. Appendix 1

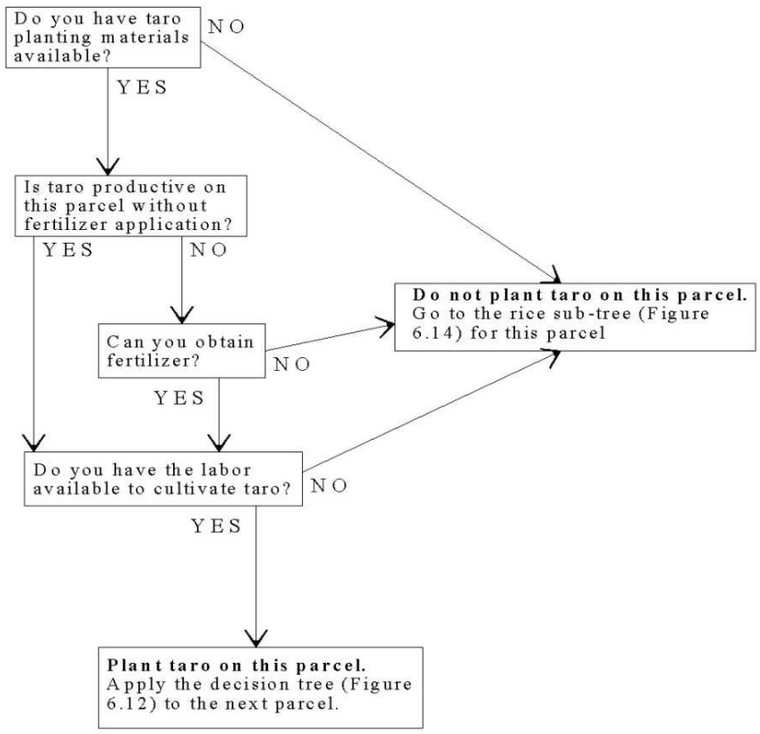
Example synthesis and inference of guiding decision-trees of agricultural information (Robotham, 1998).



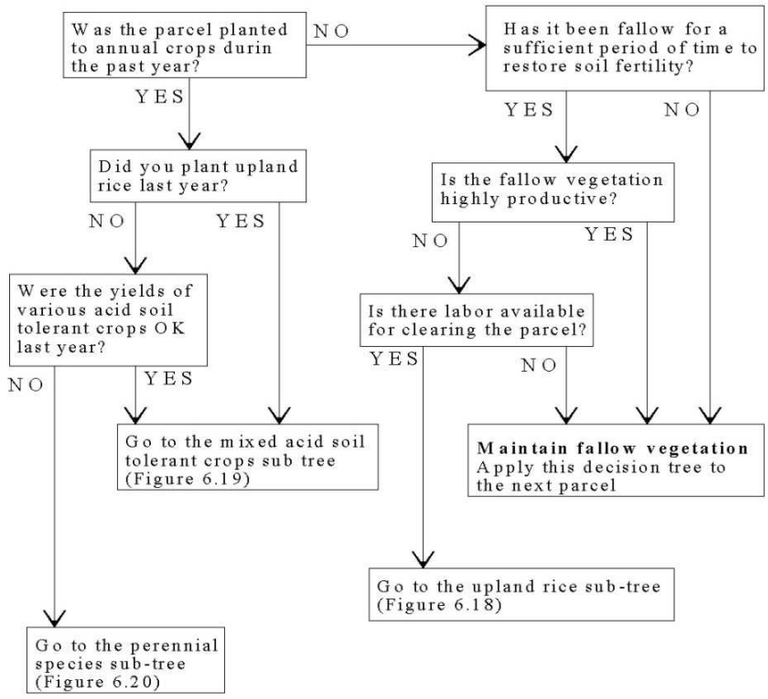
Appendix Figure 1(Robotham, 1998, Figure 6.1).



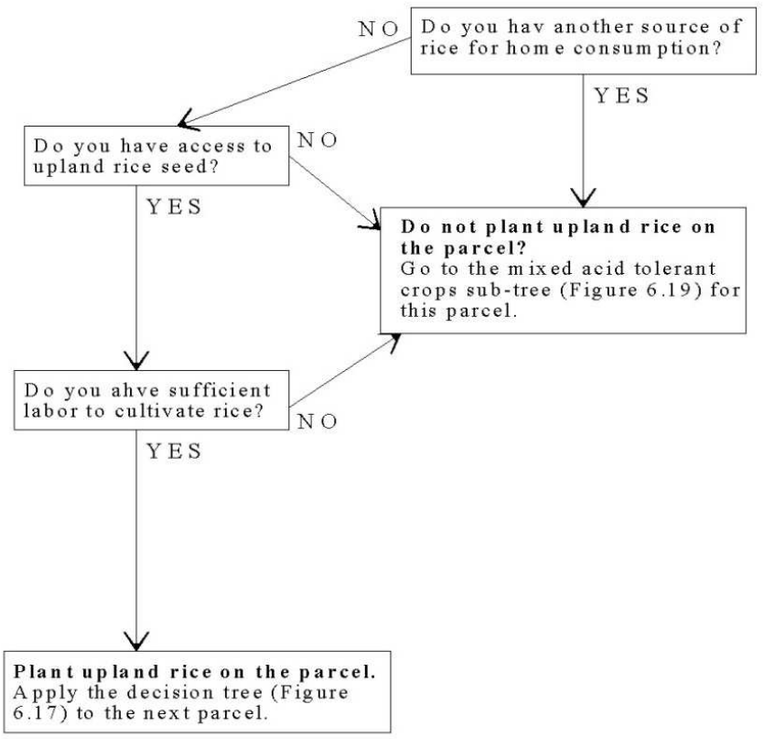
Appendix Figure 2 (Robotham, 1998, Figure 6.12).



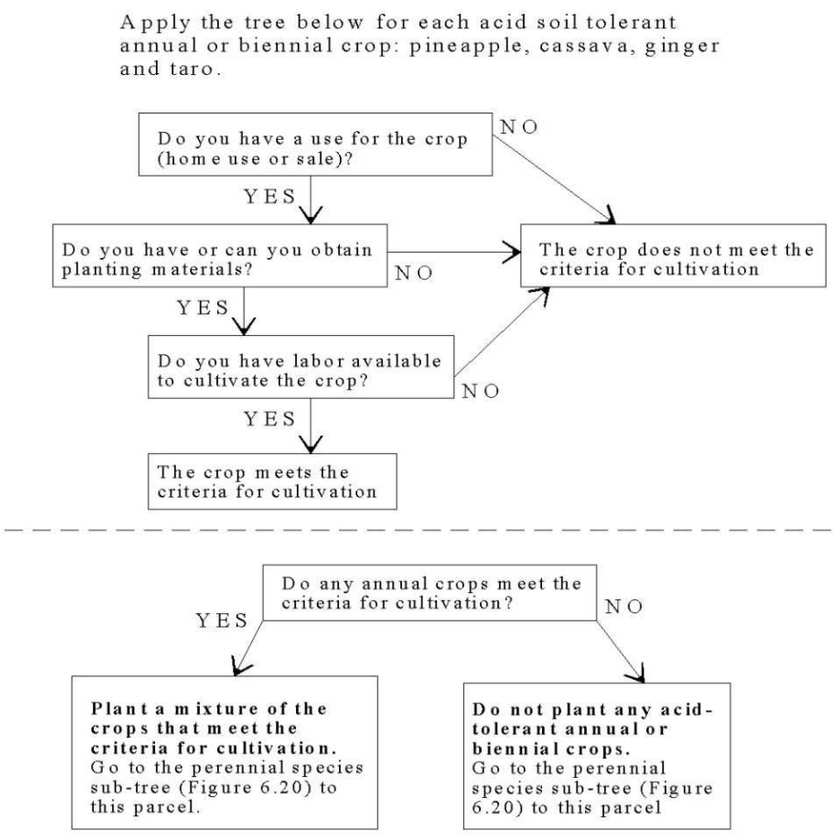
Appendix Figure 3 (Robotham, 1998, Figure 6.13).



Appendix Figure 4 (Robotham, 1998, Figure 6.17).



Appendix Figure 5 (Robotham, 1998, Figure 6.18).



Appendix Figure 6 (Robotham, 1998, Figure 6.19).

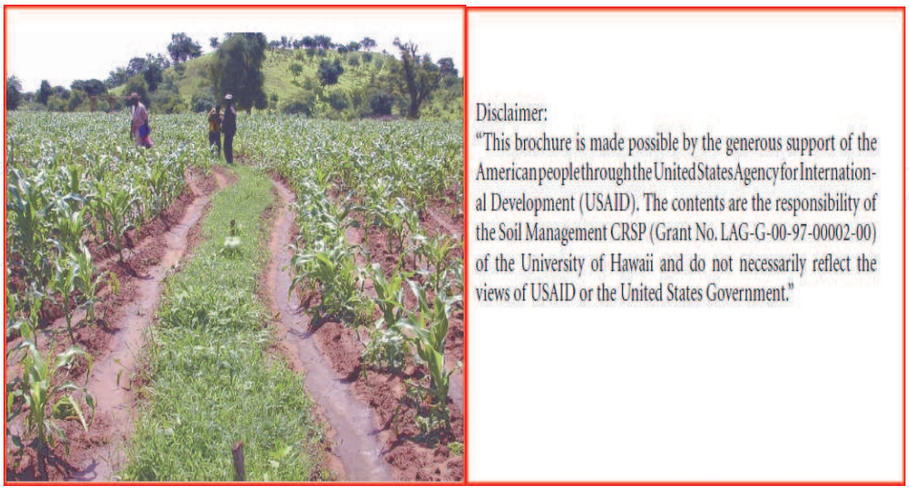
8. Appendix 2

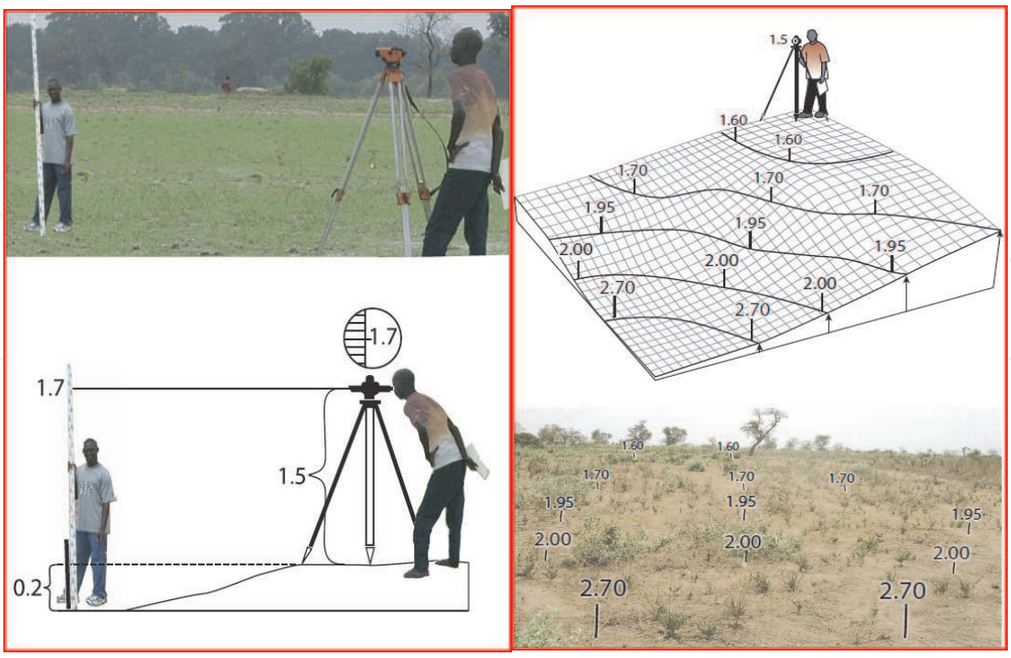
Example table illustrating the calculation of cumulative probability. Initial probability of P deficiency was considered 0.5, which on a scale of 0 to 1 indicates no information for or against P being deficient in the examined soil. The corresponding odds of a deficiency then is 50/50 or equal to 1. As various factors are considered, each with a probability of P deficiency (P(def)), the evidence accumulates until a final cumulative probability of 0.83, which indicates a high probability of P being deficient in the measured soil soil (Yost et al 1999; Pearl 1988).

Example Bayesian calculations of cumulative probability					
Initial P deficiency =	0.5	Odds (deficiency):1			
				Odds	Cum.Prob
Factor	Value	P(def)	L(def)	(def)	(P deficiency)
Agric. Region	Mali	0.6	1.50	1.50	0.60
Soil Order	none	0.5	1.00	1.50	0.60
Prev. Crop	none	0.5	1.00	1.50	0.60
Indicator Plant	Striga	0.7	2.33	3.50	0.78
Def. Symp.	Purple	0.7	2.33	8.17	0.89
Plant Anal.	0.3	0.2	0.25	2.04	0.67
Soil Anal.	< 0.5	0.7	2.33	4.76	0.83
Total Cum Probability:					0.83

9. Appendix. 3

Visual ACN

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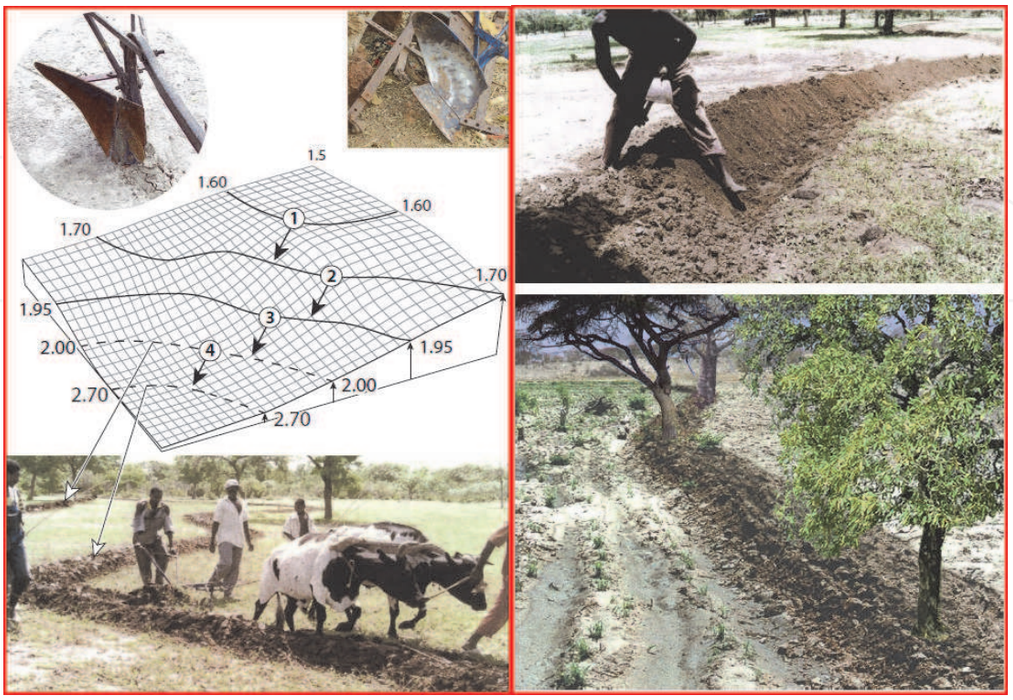
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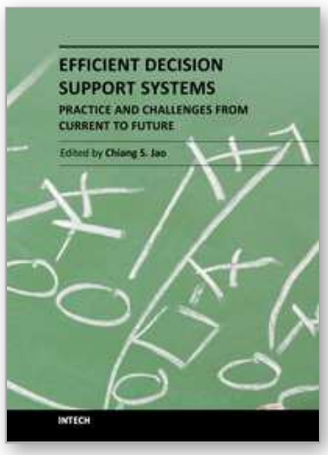

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This series is directed to diverse managerial professionals who are leading the transformation of individual domains by using expert information and domain knowledge to drive decision support systems (DSSs). The series offers a broad range of subjects addressed in specific areas such as health care, business management, banking, agriculture, environmental improvement, natural resource and spatial management, aviation administration, and hybrid applications of information technology aimed to interdisciplinary issues. This book series is composed of three volumes: Volume 1 consists of general concepts and methodology of DSSs; Volume 2 consists of applications of DSSs in the biomedical domain; Volume 3 consists of hybrid applications of DSSs in multidisciplinary domains. The book is shaped upon decision support strategies in the new infrastructure that assists the readers in full use of the creative technology to manipulate input data and to transform information into useful decisions for decision makers.

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