Methodology Development For Land Evaluation

Models Incorporating Aggregated Knowledge and Fuzzy Membership Construction

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Abstract

The most widely used methods in agricultural land evaluation are parametric methods. Unfortunately, none of them are pre-eminent. The reason for this is that parametric methods lack the ability to deal with: 1) inappropriate or incomplete data sets; 2) complex interactions between any of the factors and constraints which have not or cannot be related experimentally; 3) incorporating user information, which is generally expressed in natural language and often contains uncertainty, into models so that decisions can be made based upon both objective and subjective information. The purpose of this study was to investigate the application of fuzzy set theory along with conventional parametric methods as a possible means to overcome the above shortcomings.

Fuzzy sets theory helps to create a commonsense picture of an uncertain world. The way in which it is used in this study is by using fuzzy sets to: (1) describe the degree of membership of a variable to the system under investigation, and (2) to determine weightings to adjust for the interaction of the variables with respect to each other. The specific way the degrees of membership and weightings are derived is explained in the thesis. These were constructed into an interaction matrix. The solution of the matrix gives a numerical "comprehensive interaction index". This index can be used as a basis for: predicting rangeland production and crop yields; for measuring the comprehensive effects of all variables studied on the environment; or, for aiding a decision maker in selecting the most suitable crop for a given land unit. The index gives a measure of the interactive interplay of the variables.

The method accommodates knowledge derived from empirical experimentation and the human expert.

In this study, the use of an original multiplicative parametric method to estimate land capability for dry land agriculture and grazing in Fukang County, Xinjiang, China was studied. The results showed that the multiplicative parametric methods were reasonably successful in predicting plant production and hence land capability. However, it did indicate that a more interactive way of dealing with the operative variables would be of great advantage as the multiplicative parametric method treats each variable independently. In addition, it indicated that this method can be used only if the complete data sets are available.

A model was constructed which used fuzzy membership functions to construct an "aggregated interaction matrix" in which the summation of variables were scaled according to the way rainfall and soil variables affect water availability to plants, and hence, influence rangeland productivity. This model was used to predict rangeland production. The results indicated that this new model increased the predicability of rangeland production to 81% compared to the 61% and 67% from models using rainfall and a multiplicative parametric respectively. The results also showed that: (1) rainfall was most important in determining production at lower rainfalls (<350 mm); (2) soil texture and particularly slope were important throughout the rainfall range of 149mm to 700mm, and that (3) soil depth was only important at the higher (>350mm) rainfalls. This new method showed the potential ability to obtain knowledge from local pastoralists and experts when empirical knowledge is unavailable.

The method was also applied to predict the crop yield. The results indicated that the method, including the aggregated fuzzy knowledge, increased crop yield predicability. The accuracy was increased from 58% to 97% for field peas and from 60% to 95% for wheat compared to methods that used growing season rainfall alone. In wheat yield analysis, the results obtained using weightings derived from expert knowledge were compared with those from a least square analysis to check the reliability of this expert knowledge. The results showed that expert knowledge can be satisfactorily used to estimate local yields. This is considered important as it provides a means of estimating crop yields when data is limited, which is often the case in developing countries.

The methodology also demonstrated that these techniques can be extended into the use of comprehensive estimation for environmental impacts of agricultural land use, as well as a comprehensive evaluation for determining the selection of a preferred crop for a given set of conditions, including the biophysical, social-economic and environmental factors..

Aggregated knowledge models such as these provide a computational framework for dealing with:

(1) complex interactions which have not or cannot be related experimentally;

(2) data sets that will always remain incomplete, and;

(3) the incorporation of expert/user knowledge.

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INTRODUCTION

I. Agricultural land evaluation

Agricultural land evaluation involves assessing alternative land uses by considering the ecological potential of the land together with the suitability of the land-use from the user's perspective. During the last ten years, significant improvements have been made by incorporating mathematical modelling, together with geographic information systems, in agricultural land evaluation (Donald 1992, Bouma 1988a, Burrough 1986). This has led to a change from the traditional qualitative descriptions to a more quantitative and systematic approach. This change has been in response to the following needs:

1) agricultural land evaluation should endeavour to ensure that the land is used in a sustainable, non-degrading way;

2) land evaluation must interpret the land survey data for agricultural land planning and;

3) to improve agricultural land evaluation techniques in order to combat currents trends in land degradation.

I.I Agricultural land evaluation for sustainable land use

From 1948 to 1986, the world's grain production increased from 692 to 1839 million metric tonnes (Production Year Book (FAO) 1970, 1986, 1988). This increase was mainly achieved by the introduction of new and more productive crop varieties, irrigation, increased mechanisation, extensive use of fertilisers and pesticides, as well as the conversion of some rangeland and forest into crop land. Furthermore, some marginal lands were reclaimed for cropping in arid and semi-arid regions where land productivity depends totally upon unreliable rainfall supplemented with irrigation, if available.

This increase in food production has contributed to extensive environmental degradation and resource depletion. The serious problems of soil salinization, soil erosion and land desertification threatened the future increases (or even stabilization) of food production. The fundamental reason causing these problems is that land is exploited beyond its productive capacity.

Each land unit has its own inherent capacity for primary production. A land unit is defined as a parcel of land which has similar attributes of landform, soil and vegetation. If the land is used beyond its productive capacity, it may result in irreversible degradation and decline in productivity. If the soil properties (e.g. organic matter, water holding capability, soil structure and aeration) change sufficiently, they will limit plant growth. These degradation processes may eventually result in the soil being abandoned for cropping.

According to the United Nations (UN) projections, the World's population could reach a stationary level of some 10.5 billion by the year 2110, and the demand for food and agricultural products could be more than three times its present level (FAO 1981). The big challenge now is to ensure that agricultural development is sustainable, yet able to meet the increasing demand for agricultural products resulting from this predicted population growth.

Although the major obstacles to increasing agricultural production in many developing countries seems to be a shortage of capital investment for modern inputs, the lack of land use planning and management skills, based on an understanding of ecological limitations of the land capabilities, seriously hinders sustainable food production. Agricultural land evaluation to predict sustainable productive capacity is an important primary step in developing sustainable agricultural land use practices.

I.II Land evaluation techniques to interpret the survey data for agriculture land planning

The scientific community has not been very successful in bringing together various scientific disciplines such as chemistry, mineralogy, physics, mechanics, and the microbiology of soil, to provide a practical solution to the problems of sustainable land management. Smiles (1992, p.2) concluded that "There is some truth in the assertion that information and knowledge are available and only await determined application. There is also an element of truth in the proposition that we have passed a point of diminishing returns in many areas, in-so far as the real scientific challenge and effort lie in developing ways to apply what we know, rather than in developing deeper understanding of processes."

This is particularly true in soil science. During the last three decades great progress has been made in identifying, characterizing and mapping the world's major soils (Dudal 1978, Davidson 1992). However, the application of this soil data in development projects has been lagging far behind. One reason is that this data is often presented in a form which is not readily accessible to the potential user, or that land-use planners find it more convenient to handle economic parameters without taking physical variables into account (Dudal 1978). Nevertheless, all relevant variables need to be considered to give an integrated assessment for land use planning. Another reason is that many problems arising in land management are too difficult for simple solutions because the interactions of the variables are complicated, data sets are (and will remain) incomplete, and conditions change in space and time (Smiles 1992).

In a review of the use of soil survey data for quantitative land evaluation, Bouma (1989b) stated that soil surveys in many countries have reached a crucial stage in that increasing emphasis will be given to the interpretation and application of soil survey data. In agricultural land evaluation, information on soil, climate, appropriate crop types, pests and diseases, level of management and the economic situation have to be considered. This wide range of information and their interactions have to be understood and presented in a way which can be used by land-use planners. For example, each soil property has an effect on a particular crop. The effects of these properties have to be combined so that the overall result on crop growth can be determined. Agriculture land evaluation techniques provide a tool to interpret and apply soil data for agricultural land use planning and management.

I.III Improved agriculture land evaluation methods

During the last decade, significant changes in agricultural land evaluation techniques have occurred through to the application of GIS (Geographic Information Systems), modelling and spatial analysis (Donald 1992, Bouma 1988a, Burrough 1986). However, these technical development have not led to markedly improved management practices because: 1) the lack of means to deal with the insufficient or imperfect information; 2) failure to consider interactions between factors; 3) the failure to incorporate the land user's knowledge and requirements in the decision making process; and 4) the need for successful incorporation of the land evaluation by land managers and users in their decision making and planning.

I.III.I Deal with the insufficient or imperfect information.

When selecting an appropriate use for a parcel of land, a variety of information needs to be considered. In agriculture land evaluation, many interacting factors (biological and ecological, economic, social, and political) need to be considered. However, most of this information is characterized by imprecision or uncertainty due to the inherent complexity of the land systems considered and the existing socio-economic, political and cultural environments. In agricultural land evaluation, it is necessary to be able to deal with such complexities and imperfect information for incorporation into decision-support models.

There are several reasons for incorporating uncertainty in agriculture land evaluation. Firstly, agricultural land evaluation involves long-term considerations, e.g. rotation history, effect of soil erosion, and environmental impacts. Accurate long-term predictions are generally difficult to make and are at best only approximations of future outcomes. Secondly, most agricultural land covers large and diverse geographical areas producing multiple goods and services which are valued differently by users. Moreover, agricultural land planning often involves subjective estimates and opinions, because the relevant empirical information is unavailable. Such reasoning with vague assertions or claims generally involves uncertainties or value judgments (Kosko and Isaka 1993). Finally, agricultural land evaluation always involves incomplete data sets. This is especially true in developing counties where it may be difficult to even obtain reliable rainfall data. After reviewing the recent developments in computer models for land evaluation, Bouma (1989a) concluded that for land evaluation the major barrier was not computing capacity but the lack of data. Therefore, the development of a method that can incorporate imprecise information and deal with incomplete data sets has become a prerequisite to comprehensive agricultural land evaluation.

I.III.II Interactions among factors.

A good method should possess the ability to integrate all the determining factors which influence the results. The method also needs to reflect the interaction among these factors. Otherwise, poorly integrated information for certain land use types will ultimately lead to poor planning decisions.

Conventional approaches of land evaluation use classic methods of hierarchical classification and Boolean logic to determine land suitability classes (c.f. Soil Survey Staff 1976, Brinkman and Smyth 1973, FAO 1976, Liu and Burrough

1987). According to these methods, all land characteristics or land qualities can be split into discrete classes based on the value of certain important discriminating criteria. As the splitting does not consider the interactions among the land criteria, the boundaries for each criteria are often sharply defined. When we integrate the criteria with sharply defined boundaries together, it inevitably leads to incorrect decisions (Lui and Burrough,1987).

Studies in soil variation (Nielsen and Bouma 1985) have revealed that the " sharply defined " method of soil classes is a poor approximation of reality. Consequently, by applying an unrealistically exact model, land evaluation experts give a misleading impression of accuracy in their recommendation.

I.III.III Incorporating the land users' knowledge and requirements in the decision making process.

Agricultural land evaluation is intended to apply scientific principles to describe the land structure and function, and to give scientifically determined values for agricultural land use types. However, the land manager in most cases does not consider scientifically determined values or recommendations. The reason for this is that decisions usually do not involve the knowledge of the land managers or users. The land manager has no confidence, or may even doubt, that these decisions and recommendations can be applied to their particular situation. Therefore, we have to learn how to define problems in consultation with land managers and users in ways that permit solutions. We have to collaborate with land managers to develop systems they can understand, assess and implement (Smiles, 1992). Margan (1993) stated that in a democratic society, there was no acceptable way to make decisions without involving the users who would be affected by them. Present methods lack these qualities.

I.III.IV General adaptation by land managers and users.

Models must be flexible enough to be adapted to other regions geographical scales, crops, management practices etc. Most previous models have been constructed for specific locations. Adapting these models to other situations requires collection of new data sets, which is expensive. Therefore, we must develop models which are flexible, easy to use, and robust.

II. Literature review of land evaluation methodology.

Traditionally, there are two types of agriculture land evaluation: land capability assessment and land suitability assessment (Dent and Young 1981, McRae and Burnham 1981, Naveh and Lieberman 1984, Davidson 1992). Land capability assessment considers only the physical variables of the land that affect land-use. Land suitability assessment is a combination of the capability assessment considered together with human variables eg. the existing socio-economic and political environment as it affects the suitability of the proposed land-use.

The study of land capability assessment was founded in the nineteenth century. The development of land capability schemes during the 1930s in the USA marked the beginning of the second major stage in this subject (Davidson 1992). An earier review of American work on this is given by Hockensmith and Steele (1949). After a comprehensive handbook of land capability assessment scheme was published in USA, there was widespread adoption of this scheme. As this scheme was developed by the Soil Conservation Service of the US Department of Agriculture, it was referred to as the USDA method. The prime aim of the USDA method was not specifically for agricultural land use evaluation, but for the assessment of the degree of limitation to general land use imposed by land characteristics on the basis of intrinsic limiting land properties. A scale of land capability grades was made with the degree of limitation and hazard of erosion defining the classes. It is essentially a negative approach whereby as the degree of constraint increases, so land is allocated to lower classes (Davidson 1992). One merit of this method is that by using this scheme, land capability maps can be designed (Young and Goldsmith 1977).

Land capability maps interpreting climatic, relief and soil condition can be easily used by non-specialists. Land capability maps thus are an effective means of presenting land resource data in forms which are readily understood. Some countries modified this scheme for agriculture land evaluation purpose. A good example is British's *Agriculture Land Classification* scheme which was published in 1966. In this scheme, land is graded into five classes according to degree of limitation imposed by soil and climatic conditions on the growth of specific crops. The degree of limitation is expressed in terms of range of crops which can be grown, the level of yield, the consistency of yield, and cost of obtaining the yield (Morgan 1974).

The problem of the USDA method is that there are difficulties in determining what is technically and economically feasible. An additional problem is that technical, climatic and economic changes mean that any land capability assessment will have to be re-appraised. In a Dutch method, land capability assessment is made with reference to the economic and technological situations. The term land suitability is used instead of land capability(Vink and van Zuilen 1974). Thus, as with the USDA method, various assumptions of technical and economic constraints are necessary before land or soil grading is made. Changes in these assumptions mean that the suitability assessments need to be re-appraised.

By 1970, many countries had developed their own land evaluation systems (Dudal, 1978). These systems were developed for different land uses, and they are very different in scope. The FAO feared that major problems of information exchange would result, and in 1970 a working group was set up to develop a framework for land evaluation. The result was published with the title of "FAO Framework for Land Evaluation" (Beek 1978). In this framework, two schemes were developed for agricultural land use. They were for rainfed agriculture and irrigated agriculture. This framework was devised for an international standard and especially for the development of a classification system which allowed a comparative evaluation for the different uses that can be made on the same land (Dudal, 1978).

The FAO framework and USDA land capability schemes provide guidelines for land evaluation. The quality of the evaluation results, however, depends on data availability and the method for handling the complexity of the information from the land system.

The most widely applied methods in agriculture land evaluation are the parametric methods (Davidson, 1992). After evaluating the land productivity in Bulgaria, Garbouchev *et.al.* (1971) concluded that land productivity evaluation should be studied mainly by parametric methods.

The parametric methods include two steps: (1) to evaluate separately the different properties of land and, by a statistical analysis, give them separate numerical valuations according to their importance within and between each other; and (2) to combine these properties according to a mathematical law taking into consideration the relationship and the interactions between the properties to produce a final index of performance. This index is essentially an integrated numerical summary of the land characteristics considered. It is used to rank land in order of (agricultural) value, such as the land capability index. This focuses upon the nature and degree of limitation imposed by the physical characteristics of a land unit for a certain use. It also gives a productivity index which refers to the physical yield that would be expected from a given use on a particular land unit.

Historically, the first application of a parametric method seems to have been made by Fackler (Riquier 1972) in Bavaria. This extremely simple method, later adopted as a reference for land taxation, is based on the addition of a few factors only - humus content, soil depth etc. It is clear that this method is too simple for use in practical conditions.

Including more complexity, an addition and substruction method was used in Romania (Teaci, 1964, 1970). Compounded factors, such as slope and the total phosphorus content, were included. This method assumed that all the favourable factors add together while all the unfavourable factors subtract from the total. It was considered that the climate, the relief, and the hydrological conditions contribute 26, 20 and 20 percent of the final score, respectively. The soil component covers the remaining 34 percent of the productivity. This assignment of influence on the final rating may be appropriate for Romania, but is not equally applicable elsewhere. This method is obviously location-specific.

The multiplicative method was an improvement as it incorporated the law of the minimum (Riquier 1972). Yield is limited by the lowest factor. If it is an absolute limit to production, it will be indexed "0". This method of calculation appears realistic and conforms with experimental data.

The first demand for multiplicative method arose from the need for objective quantitative standards in determining land taxes (Beek 1978). The Storie Index (Storie 1937) was developed for this purpose in California. The index rating was obtained by multiplying ratings based on factors such as type of soil profile, texture of surface soil, and modifying factors such as drainage, slope or alkalinity. This method has been gradually revised over the years with slope being introduced as a separate factor, with more classes for soil profile development and with slight changes in scores for other component variables (Storie 1976). For example, Sys and Frankart (Riquier 1973) developed a multiplication method for the soils of the humid tropics. It considered the following criteria: profile development, parent material, depth, colour, drainage, pH, base saturation and development of A1 horizon of soil. Like the Storie Index, the profile factor actually refered to the type of soil with reference to the soil series of that region. Consequently, other indices must be proposed for other regions whenever different soils occur. The problem of location-specificity therefore still exists.

Steeley *et.al.* (1985) proposed a multiplication method for estimating primary production in rangelands of steppe regions. This method multiplies the relative productivity index of some easily measurable properties of land such as rainfall, slope, soil depth and salinity, to obtain an index of relative available soil moisture. As these land characteristics are widely recognised as the main factors determining available soil moisture in rangeland of steppe regions of the world, this method could be easily adopted elsewhere to estimate relative primary production. However, if the correlation between the index of available soil moisture and land productivity is established, the constants in the correlation, which are normally tested statistically from a local yield data bases, may have to be redefined for application in other localities (see chapter 1).

Another problem with a multiplicative approach is if component scores are very low or high, they have a considerable impact on the overall index (Davidson 1992). This could result in weak relationhips between the overall index and land production. This problem could be minimized by taking a cube root as demonstrated by Koreleski (1988). However, the fundamental cause of this problem is not only the intrinsical property of the multiplicative approach but also sharply defined boundaries of each component score. In reality, as the components interact on each other, the boundaries of each component score are vague rather than sharp. When data sets with sharply defined boundaries have been combined using the parametric method, considerable loss of information could lead to the final result being out of keeping with the objective conditions. For example, the method developed in the Poushkarov Institute (1970) of Sofia considered the water table level lying between 0 and 300 mm as prohibitive and indexed 0 accordingly, although it is obvious that a water table level of 299 mm does not imply zero productivity.

From the literature review it can be concluded that many parametric methods already exist. Unfortunately, none of them are pre-eminent. It must be noted that considerable improvements have been made to these methods with respect to the number of productivity factors considered and the adoption of the multiplication procedure. However some disadvantages highlighted are:

- Ratings developed and tested in one area for a specific crop may have to be redefined for application in other localities (McRae and Burnham 1981). This is always associated with large and expensive survey requirement for specific regions which makes it prohibitive for many regions in developing countries. The data may often inadequate and incomplete. It is believed that the most difficult point to overcome is to develop and adapt internationally approved methods with worldwide applicability (Riquier 1972, McRae and Burnham 1981).

- There is a danger that a parametric system can be assumed to give an objective measure (McRae and Burnham,1981). This is especially true when we apply this method for land suitability analysis. As the methods do not involve the land-user in the decision- making process, the land-user may have little confidence and trust in the decisions and the recommendations that are produced. These recommendations would subsequently have reduced a likelihood of being successfully implemented and maintained.

- A crucial problem is the interaction between the variables that affect land uses. When we evaluate land by these criteria with sharply defined boundaries, the failure to consider these interactions could lead to incorrect results.

III. The purposes of this study

The purpose of this study was to apply fuzzy set theory to the parametric method so that the resulting new method would have the ability to deal with:

1) inappropriate &/or incomplete data sets;

2) complex interactions between any of the factors & constraints mentioned above which have not or cannot be related experimentally;

3) incorporate user's information, which is always expressed in natural language and often contains uncertainty, into models so that decision could be made based upon both objective and subjective information.

Fuzzy set theory is specifically developed for dealing with inexact concepts such as unclear boundaries and the use of natural language information in which the central concepts are present, but where edge definitions are necessarily vague. Many practical scientists recognise that exact, rigid empirical models result in inconsistencies and they prefer to use descriptive natural language such as 'moderately well drained, shallow, few, important, more or less'. These types of words and phrases are used a great deal in the soil survey and land evaluation literature (Lui,1987; Burrough,1989). However, too much flexibility leads to anarchy and too much rigidity causes conflict. Clearly we need a model that tolerates inexactness in the data and the models to be expressed, while at the same time maintaining adherence to systematic principles. The new method is expected to have two features:

- It can incorporate human empirical knowledge in the model, which is normally derived from: (1) the local specific circumstances; (2) the local expertise and (3) previously published literature. This approach could reduce the data demand when adopting the model to a different area as many fundamentals may be common, thus reducing the expense of surveys. Also, when data sets are inadequate and incomplete, expert knowledge can be incorporated so that method could be generally adapted in other areas by land managers and users.

- In this model, a membership function of a fuzzy set, which is a generalisation of Boolean algebra to situations where data are modelled by entities whose attributes have regions of gradual transition rather than sharp boundaries, allows us to deal with the uncertaint information about a boundary of change. This approach could reduce information loss when we integrate each component together to get the final index.

- Finally, this method is extended to consider social-economic issue and environmental impacts of alternative land use in formulating a comprehensive evaluation model for agricultural land use.

IV. Method

This method involves two techniques. Firstly, a Fuzzy membership function is used to represent the contribution relationship of each factor to the final index. Secondly, the inclusion of the parameters in the integrated parametric model that consist of interaction matrix division and weighting assignment according to assessment of the importance of the variables with respect to each other in determining an outcome.

IV.I Fuzzy set theory and its membership function

The theory of sets was developed by the mathematicians Boole and Cantor in the nineteenth century. Intuitively, a set is a well-defined collection of objects or ideas. These objects or ideas are called the elements or members of the set. They can be represented in nature language or numbers. The definition of a set can be represented by using the membership function $u_A(x)$ which defines the grade of membership of x belonging to A:

As an example, the members of the board of research directors of a university are Smith, John, Dave, and Mark. The set can be represented as either:

$$A = \{ \text{Smith, John, Dave, Mark} \}$$

or:

$$A = \{ x \mid x \text{ is a member of the board of research directors} \}$$

The membership function of the set can be defined as following:

$u_A(x) = 0$ if x does not belonging to A

$u_A(x) = 1$ if x belongs to A

This definition means that to any given set and its elements, the elements either belong to the set or not. If an element belongs to the set its membership function is 1; if an element does not belong to the set its membership function is 0. There is no element which is in an intersection or in between. However, in practical situation, elements are not always either 1 or 0 because the object is not always clearly defined. As an example, as a "director", a person can be quarter-time, half-time and three-quarter-time "director". That means that this person is between being "a full time director" and "not a director". Therefore, the definition of this person being a partial member of several boards of directors is beyond the ability of classical set theory.

The problem to deal with poorly-defined objects and classes is not unique to soil science and land evaluation, but is a wider part of human experience (Liu, 1987). As traditional set theory has no sensible way to handle such imprecision, Zadeh introduced 'Fuzzy sets' as a means for dealing with inexact concepts (Zadeh 1965, Zadeh 1975, Negoita 1985 and Liu 1987). Unlike traditional sets, fuzzy sets were used to define a type of imprecision characterizing objects, that for various reasons, cannot have, or do not have, sharply defined boundaries. Unlike classical sets theory, the membership between the set and element can take any value between 0 and 1. In another words, an element is not exclusively belonging to the set or not, but can be a partial member or element of the set. Whenever we have to deal with ambiguity, vagueness and ambivalence in mathematical or conceptual models of empirical phenomena, it is appropriate to use fuzzy sets.

The following introduction of basic fuzzy sets theory is based on the text written by Kandel (1986) and has been used by Burrough (1989) for soil survey and land evaluation. Fuzzy set theory distinguishes three kinds of inexactness:

(a) generality, where a single concept applies to a variety of situations;
(b) ambiguity, where a single concept embraces more than one distinguishable sub-concept;
(c) vagueness, where precise boundaries are not defined.

A fuzzy set can be defined mathematically as follows: If $X = \{x\}$ denotes a space of objects, then the fuzzy set A in X is the set of ordered pairs

$$A = \{x, u_A(x)\} \qquad x \in X$$

where $u_A(x)$ is known as the ' grade of membership' of x in A and $x \in X$ means that x is contained in X.

Usually, $u_A(x)$ is a number in the range 0 to 1, with 1 representing full membership in a set and 0 representing non-membership. The grades of membership of x in A reflect a kind of ordering that is not based on probability but on admitted possibility. The value of $u_A(x)$ of object x in A can be interpreted as the degree of compatibility of the predicate associated with set A and object x; in other words $u_A(x)$ of x in A specifies the extent to which x can be regarded as belonging to A .

The membership function of a fuzzy set defines how the grade of membership of x in A is determined. It is used to describe the vague characteristic of a fuzzy set. The assignment of the membership function of a fuzzy set should ensure that the grade of membership is 1 at the centre of the set and that it falls off in an appropriate way through the fuzzy boundaries to the region outside the set where it takes the value 0. Therefore a membership function could be used to describe any distribution of membership grades between the set and elements. For example, the membership function defined in this thesis for the soil pH suitable for growing wheat is :

$$u(x) = \begin{cases} 0 & for \quad x < 4.5 \\ 1 - \dfrac{6.5 - x}{2} & for \quad 4.5 \le x < 6.5 \\ 1 & for \quad 6.5 \le x < 8.0 \\ \dfrac{9.5 - x}{1.5} & for \quad 8.0 \le x < 9 \\ 0.33 & for \quad x \ge 9 \end{cases}$$

where $u(x)$ is the grade of membership related to the degree of suitability of a given pH, x, for growing a wheat crop.

IV.II The interaction matrix

Graded membership of $u(x)$, for a given value of x_i gives a measure of degree of the belonging of x_i in a set A. The degree of belonging is rule-based. If x_1, $x_2, \cdots\ x_n$ are members of the set A, then degrees of membership of x_i can then be defined relative to these members on a scale of 0 to 1 (this scale being chosen for uniformity).

The rules governing graded membership are determined by the relationship between members of the set (e.g. linear, cubic, hyperbolic etc.) where an overall result is determined by the interplay of various sets. The graded membership of the given values in the sets are interrelated by weightings which give estimates of the possible importance to the sets, given by the graded membership, with respect to each other in determining an outcome. This is accomplished using an interaction matrix where the weightings (W_n) form a horizontal vector and the graded memberships (D_n) a vertical scalar.

For example the interaction matrix:

$$\begin{pmatrix} w_1 & w_2 & \dots & w_n \end{pmatrix} \begin{pmatrix} D_1 \\ D_2 \\ \dots \\ D_n \end{pmatrix}$$

where W_1, W_2,...W_n are weightings and D_1, D_2,...D_n are the graded memberships of the variables in the sets considered.

The result of this matrix gives a comprehensive index of interaction of the sets.

IV.III Weighting assignment

A horizontal vector in an interaction matrix represents the weightings for each factor (or element) according to the assessment of its importance with respect to the others in determining an outcome. Where experimental data exists, it can be used to determined this horizontal vector. However, where the data sets is incomplete or does not exist, a local expert could assign the weightings according to their empirical knowledge and experiences. When these weightings are determined by local experts, this approach makes the model easily adapted to different situations. It also provides users with the opportunity to express their own opinions.

To help the user in making weight assignment, we use table 1.

Considered Importance of a Variable	**Value Assigned**
Least important	1
Marginally important	3
Important	5
Very important	7
Most important	9

Values were chosen from this table to represent the considered importance of a variable (V_i). The weighting W_i of a variable was thus determined by:

$$W_i = \frac{V_i}{\sum_{i=1}^{n} V_i}$$

where: W_i = the weighting of the variable v_i

V_i = the value of the considered importance of the variable v_i.

$\sum_{i=1}^{n} v_i$ is the sum of the considered importance of the values **for the number of variable**. This method is similar to that described by Saaty (1978).

IV.IV Multi-level interaction matrix

Most of the interactions between variables in a system are very complicated. When we evaluate the system many factors influence a final outcome and each need to be considered. Such factors may also exist at several levels of influence. If the user is going to assign weights for each factor with respect to each other, it is not easy to induce a reliable weighting set from the user if we consider all the factors together. The reason is that the human mind has more confidence comparing the relative importance of factors in small groups rather than large ones. Therefore, in this current method, the whole factor set is divided into several small sets according to their properties so that the user can assign the weighting within each small group of factors. Subsequently, weightings can be assigned to each group.

V. Thesis Contents

Chapter 1 describes the use of an original multiplicative parametric method to estimate land capability for dry land agriculture and grazing in Fukang County of China. It develops a way of accounting for the contribution of high ground water tables that increase the water available to plants and hence increase production. The method was reasonably successful in predicting plant production and hence land capability. However, it did indicate that a more interactive way of dealing with the operative variables would be of great advantage, and also that the method could only be used if the data sets are available.

Chapter 2 explores the use of fuzzy membership functions to construct an aggregated interaction matrix to investigate the way rainfall and soil variables affect water availability to plants, and hence, influence rangeland productivity. Aggregation of variables gives a comprehensive value which can be used to predict production. The model increases the predicability of production to 81% compared with models using rainfall alone and a multiplicative parametric, which produced predicability values of 61% and 67%, respectively. The results also showed that: (1) the rainfall was most important in determining production at lower rainfalls (<350 mm); (2) soil texture, and particularly slope, were important for the rainfall range 149 to 700 mm, and that (3) soil depth was only important at the higher (>350 mm) rainfalls. This new method indicated the potential to obtain useful information from local pastoralists and experts when empirical knowledge is available.

In Chapters 3 and 4, this new method was employed to predict crop yield. The results showed that including the aggregated fuzzy knowledge from local experts increased crop yield predicability to 97%, compared with 58% using traditional models for field peas, and from 60% to 95% for models that depended upon growing season rainfall alone for wheat.

The results obtained using weighting's derived from expert knowledge were compared with those from a least square analysis. The results revealed that expert knowledge can be effectively used to estimate local yields. This is considered important as it gives a means of estimating crop yields when data is limited, as is often the case in developing countries.

Chapter 5 presents examples of how the interaction matrix is extended to derive a comprehensive estimation of the environmental impacts of agricultural land use. The outcome of this model is to derive an overall assessment index of environmental impact for a number of alternative crops with different management practices. The impacts are divided into three groups: soil degradation; water pollution; and soil erosion. Each group has its own sub-matrix which further considers the land characteristics such as slope, soil texture, depth of soil, proximity to drainage lines, and management practices such as cultivation intensity, stubble retention and type of tillage. The model has been developed in response to the need to apply what we know in an effectively integrated comprehensive way and as an aid to managing our land resources in a non-polluting and sustainable way.

Chapter 6 presents a comprehensive evaluation model. This model, which also use the same methodology, provides a way to determine a preferred crop for given conditions with the consideration of biophysical, social-economic and environmental effects.

Chapter 1. LAND CAPABILITY OF FUKANG COUNTY, XINJIANG PROVINCE

Use of a parametric model

This work proposes a new method for estimating the relative available soil moisture (RAM) to support plant growth. This is used as a means of determining land capability from the annual primary productivity that a parcel of land can support. The method determines the RAM in a multiplicative parametric fashion from rainfall plus the contribution from ground water, soil depth, texture, slope and salinity.

1.1 Introduction

In arid and semi-arid environments throughout the world, the main determinant of annual primary production is the annual rainfall (Le Houerou, 1984). Le Houerou (op. cit.) defined the Rain Use Efficiency (RUE) as the quotient of annual above ground biomass by annual rainfall, i.e. the number of kilograms aerial dry matter production over 1ha in one year per millimetre of total rainfall. He also reported that production depends on soil condition, although not measures of how soil factors affected the RUE were presented.

The current work describes the use of a method which gives a measure of land capability from a calculation of the relative available soil moisture (RAM). The RAM is used to give an estimate of the annual primary productivity.

The method uses annual rainfall, soil depth, salinity, slope and texture in a parametric way to calculate RAM. It has been used in semi-arid steppic regions of the Mediterranean Basin of North Africa Steely *et. a*l. (1986) and developed further by Thomas and Squires (1991). The method was necessary in this region as the vegetation is generally so sparse, over-utilised and degraded that it is difficult to estimate land capability (Thomas et al 1986). This study was conduted in the Fukang region of China where consideration had to be given to the effects of high ground water tables on the RAM (L i 1990).

1.2 Methods

Rainfall Isohyets

The rainfall isohyets for the region were calculated from the relation:

$$Rf = \frac{A - 35.7}{3.48} \qquad (1.1)$$

where Rf = rainfall in mm

A = Altitude in m

This relation was derived from data collected over 10 to 20 years from 40 stations on the northern side of the Tianshan mountains. It gives an R^2 of 0.71. Rainfall did not change with latitude or longitude only with altitude (Sun, 1991).

Relative Available Soil Moisture (RAM)

$$RAM = (k_1 \times k_2 \times \ldots\ldots \times k_n)\ Rf + Gw \qquad (1.2)$$

where RAM = relative available soil moisture(mm) for plant growth.

Rf = annual rainfall in mm.

Gw = the contribution of ground water to the RAM.

$k_1 \times k_2 \ldots\ldots \times k_n$ = Relative production indices (RPI) for soil depth, slope, salinity and texture. These range from 1 to 0 and give weightings for the way each soil parameter affects the RAM. These are given in Steeley *et. al.* (1986) and Thomas and Squires (1991). The weightings given to the relative production indices are shown below.

Ground Water Contribution, Gw

This was calculated from the following relationship:

$$Gw = \frac{E_T}{d^2} \tag{1.3}$$

where Gw = The annual ground water rise though the soil profile, mm.

d = depth to ground water (m).

E_T = surface evaporation constant from the soil which depends on soil texture in the following way:

Soil texture	E_T
loam	117.75
clay	63.93
sand	343.1

The rise through the soil is due to capillary action, with evaporation occurring at the soil surface.

This relationship was obtained from a regression of evaporation against ground water depth over many years of study (Fukang Hydrology Station, 1986).

Potential Yield

This was calculated from the following relationship:

$$Y_{ep} = 2.33\ \mathrm{RAM}^{1.09} \tag{1.4}$$

where: Y_{ep} = annual dry matter production at ecological potential ($\mathrm{kg\ ha^{-1}\ yr^{-1}}$).

RAM = relative available soil moisture.

2.33 = a constant which represents the water use efficiency i.e., kg dry matter production annually per mm of rainfall.

The relationship was derived for shrub steppe communities (Le Houerou and Hoste, 1977; Steeley et al., 1986).

Index of Floral Composition IFC

$$\mathrm{IFC} = \frac{\sum \mathrm{FC\ (of\ all\ desirable\ perennials)}}{\sum \mathrm{FC(all\ perennials)}}$$

where: FC = foliage cover.

The foliage cover was measured by the step-point method (Cunningham, 1975). This relationship provides a measure of the state of the vegetation for grazing. The greater the component of non-desirable species (e.g., non-palatable and toxic plants) in the vegetation the lower is the IFC, and similarly, the suitability of the land for grazing.

Land Capability Class (LCC) and Use with respect to RAM.

Figure 1.1 gives the RAM calculated from equation 1.2. These are divided into ranges of 100 mm. The possible land uses are presented for these 12 LCC's in Figure 1.1.

1.3 Study Area

Location

Fukang County is situated 75 km NW of Urumqi, capital of the Xinjiang autonomous province of China (87°45' to 88°05'E, 43°50' to 44°30'N) it is situated in the narrow steppic band approximately 40 km wide, bounded by the Tianshan mountains to the south and the Kurbantungute desert to the north. (Fig1.2).

Topography of Fukang County

The main features are the foothills of the mountains 3 the top and middle 5 of the alluvial fans and the saline alluvial plains 6 and the sand dunes 7 (Figure 1.2). Elevations range from about 450 m in the sand dunes to about 1300 m in the foothills. Figure1.3 is a schematic cross-section of the region.

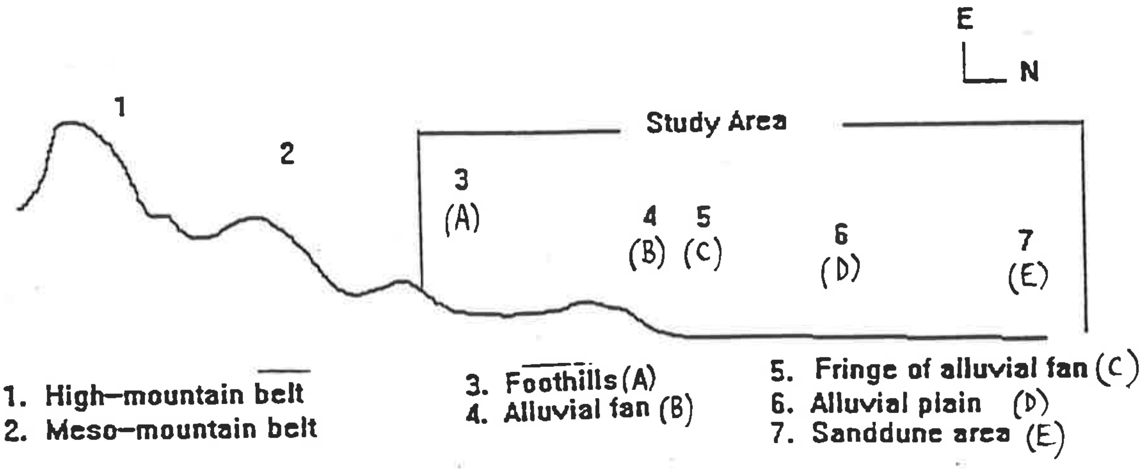


Fig 1.3 Schematic Cross-Section, Fukang County

				Possible Intensity of Land Use					
				Grazing			Dry Land Farming		
RAM Range (mm)	Land Capability Class	Conservation	Foresty	Extensive	Medium	Intensive	Low	medium	High	Very High	Mean Production (kg.ha-1 an-1)
>800	1	■	■	■	■	■	■	■	■	■	1980
700--800	2	■	■	■	■	■	■	■	■	■	1747
600--700	3	■	■	■	■	■	■	■	■		1514
500--600	4	■	■	■	■	■	■	■			1280
425--500	5	■	■	■	■	■	■				1078
350--425	6	■	■	■	■	■	■				903
275--350	7	■	■	■	■						728
200--275	8	■	■	■	■						553
150--200	9	■	■	■							408
100--150	10	■	■	■							291
50--100	11	■									175
0--50	12	■									58

Fig 1.1 ARM, LCC and their possible land use types

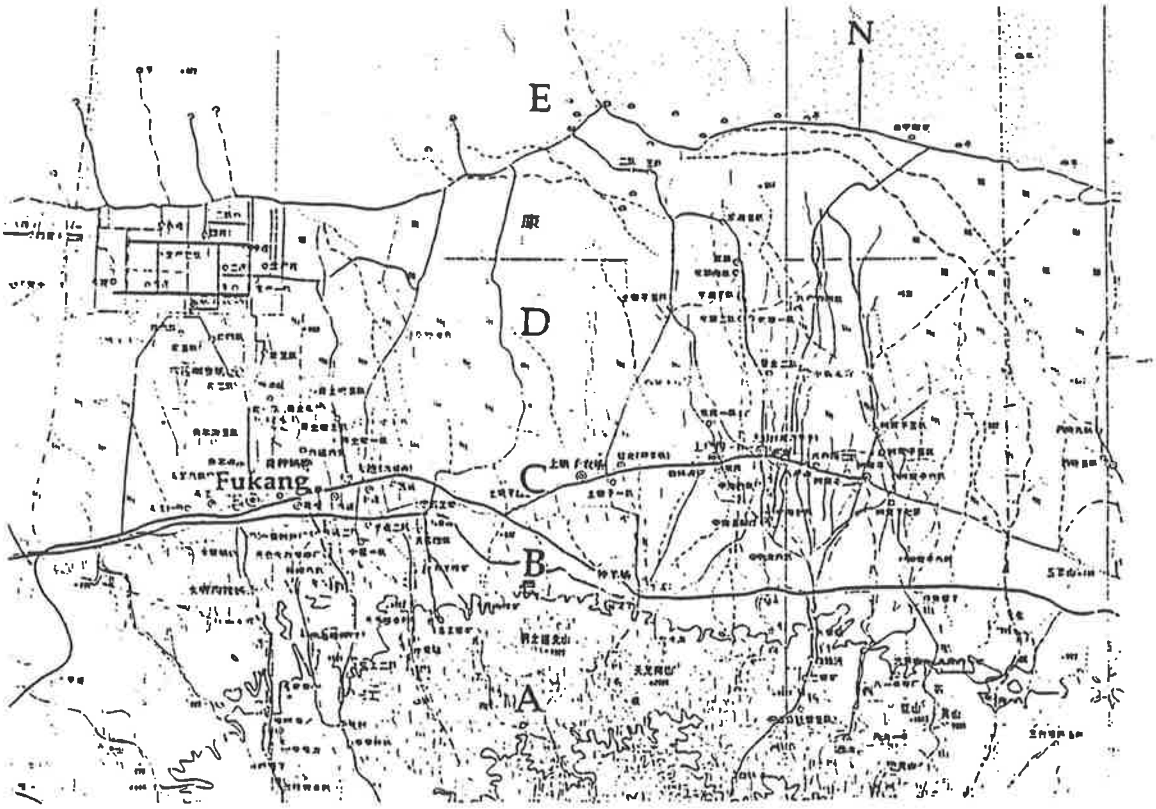


Fig 1.2 Topographic map of Fukang County

Temperature

The winters are cold and summers are hot. The mean annual temperature is 6.1 °C. The lowest temperature is in January with a mean of -18.8°C and the highest temperature is in July with a mean 25.6°C. The day-night temperature difference is high, averaging 17.7°C.

Land Use

The main landuse in Fukang County are described in Table.1.1:

The high stocking pressure in the foothills and alluvial fans is due to the restricted area available.

Irrigation permits winter-spring wheat and cotton to be produced in the new alluvial plains area. The irrigation is mainly without drainage and is of low efficiency. There has been a 10% loss of productivity with 1,000 ha removed from production due to salinisation (Li Shugang and Wang Zhongion, 1990). Grazing productivity has increased in the area of high permanent water tables mainly due to *Tamarix spp.(T.laxa Willd., T.ramosissima Ldb., T.elongata Ldb., T.leptostachys Bge. and T.hohenackeri Bge.).*

The sand dune areas are the most stable in China resulting from the high cover of *Haloxylon spp (H.ammodendron Bge and H.persicum Bge.ex Boiss)* due to the high water tables extending into the dune area from the alluvial plain and alluvial fans. However, this fragile system must be managed very carefully to prevent mobilisation of the sand dunes and drift of sand onto the irrigation areas.

Table 1.1: Landscape Type and Utilisation

Landscape Type	Utilisation	Comments
Foothills	Contains some highly productive valleys which could be used for dryland farming and fodder production. Winter grazing under light snow cover, plus 3 to 4 months spring and autumn grazing. Contains some highly productive valleys.	Limited area results in high stocking rates. Overgrazing and loss due to trampling. Very early spring grazing results in loss of productivity.
Top and middle of alluvial fans	Spring and autumn grazing for 4 months.	Heavy overgrazing due to restricted area resulting in high stocking rates and long periods of grazing in spring and autumn. Very early spring grazing results in loss of productivity.
Bottom of the alluvial fans	Mostly irrigation farming of winter and spring wheat plus cotton for 5 months during the year. Some hay cutting during autumn.	Water table can be high. High water tables can increase moisture availability to deeper rooting plants resulting in high productivity.
Saline Alluvial Plains	Grazing in early spring and late autumn for approximately 2 to 3 months.	Productivity is limited by salinity except for salt tolerant species. Many species are of low palatability or not palatable. Grazing is limited by lack of stock watering points. Grazed by camels throughout the year.
Sand Dunes	Winter grazing for 4 months. Swales used for sheltered lambing area and fuel collection.	Summer, spring and autumn grazing is not possible except for camels due to lack of drinking water. Fragile systems, danger that overgrazing and excessive fuel collection could result in mobilisation of the sand dunes. The main stabilising component is the open high cover of deep rooting *Haloxylon species*.

Vegetation

The landscape type, vegetative cover components, and their palatability are given in Table1.2. The index of floral composition (IFC), soil type, soil textures, soil salinity and measured annual biomass production are given in Table 1.3 (Sun, 1991).

The principle landscape types and associated vegetation are:

Foothills: These are a low shrubland. The main cover component of the perennial vegetation is *Seriphidium transillense*, and *Nanophyton erinaceum Bge.* which are of medium palatability. The 10.3% perennial cover is rather low considering the rainfall (350 to 450 mm). This could be the result of over-grazing in this area (Table1.1).

The IFC value of 0.95 indicates that there is no invasion or increase in less-desirable and non-desirable perennial species. Salinity is relatively low due to the higher rainfall and steeper slopes.

Though the ephemeral cover is relatively high, the 38.9% bare soil (Table1.2) combined with the steeper slopes means that the foothills are moderately prone to accelerated erosion.

The actual annual biomass production of between 750 to 836 kg ha^{-1} yr^{-1} compared to the calculated potential of 850 to 980 (Table1.4) suggests that this land system is producing at about 90% of its potential.

Top and middle of Alluvial Fans: The main perennial cover components of this low shrubland is *Reaumuria soongorica Maxim* which is consistent with

Table 1.2: Vegetation, foliage cover and palatability (Sun, 1991)

Cover Component	Palatability	Foliage cover %								
						Sand Dunes				
		Foothills	Total and middle of Alluvial Fans	Bottom of Alluvial Fans	Saline Alluvial Plain	Cross-dunes	Dune Crests	West Slope	East Slope	Swale
Seriphidium transillense	M	6.3	0.4							
Nanophyton erinaceum Bge	M	3.1	0.1							
Reaumuria soongorica Marix	M		8.4							
Tamarix spp	N		0.1	0.5	5.5					1.7
Nitraria siberica Pall	N		0.1		1.3					
Kalidium foliatum Moq	L		0.5		1.1					
Haloxylon ammodendron Bge &H.persicum Bge	L		0.4		0.6	13.7	4.6	16.5	18.1	20.7
Suaeda dendroides Moq	N	0.5	1.4		0.2					
Aristida pennata Trin	U					0.1	2.7			
Artemisia. terrae-alba Krasch	H					0.4	1.1	1.2	8.1	
Calligonum leucocladum Bge	M					1.2	2.6	3.4		
Chondrilla piptocoma	M					0.2	0.7	1.0		
Ephedra distachya L	N					0.2	7.3	0.2		
Achnatherum splendens Ohw	M			12.7						
Limonium aureum Hill.	N			15.5						
Leymus sccalinus Tzvel	H			8.9						
Aeluropus litoralis Parl	M			17.5						
Phragmites communis Trin	M			12.2						
Plantago minuta Pall	M			2.0						
Halimodendron halodendron Voss	M			0.9		0.4			0.8	
Other		0.4	0.1	0.8		0.2	0.2	1.6	0.2	0.8
Lichen			19.7		6.1	24.7	3.3	13.7	3.6	40.9
Ephemerals		38.4	34.9	20.5	8.0	4.0	8.2	19.9	27.4	
Litter		12.2	7.7	2.5	13.2	18.6	5.3	30.3	35.5	29.0
Salt % of area					23.3					
Bare Ground		38.9	26.0	6.0	40.0	36.3	64.0	13.7	4.8	7.5
Dung of grazing		0.2	0.2		0.7					
Total Perennial (%)		10.3	11.4	71.0	8.7	16.4	19.2	22.5	28.6	22.6

Palatability: H=High M=Medium L=low N=Non palatable U = Unpalatable

Table 1.3 Index of Floral composition (IFC), soil type, soil texture, soil salinity and measured annual biomass production

					Sand Dunes				
Characteristics of landscape	Foothills	Tope and middle of Alluvial Fans	Bottom of Alluvial Fans	Saline Alluvial Plain	Cross-dunes	Dune Crests	West Slope	East Slope	Swale
I.F.C.	0.95	0.86	0.78	0.72	0.99	0.56	0.99	0.92	1.00
Soil type	Mesic, Lithic Camborthids	Mesic, Fluventic Camborthids	Mesic, Fluventic Camborthids	Mesic, Typic Salorthids	Utic Torripsamments				Aquic Ustipsamments
Soil Texture	CL	SC to CL	CL	CL, LCM, SCL	S	S	S	S	SL
Soil Salinity (mS)	1.77	1.20	4.31	8.32		0.046			0.106
Measured Biomass Production (kg ha^{-1} yr^{-1})	750-836	380-400	650-1200*	750-965			250		

Soil Texture Code: c=Clay L=Loam M=Medium Si=Silt S=Sand

* High production due to deep rooting Haloxylon and Tamarix which reach the ground water table.

Table 1.4: Land Capability Elements

Landscape Type	Mean Annual Rainfall (mm)	Relative Productivity Indices			Available Moisture ($RAM^{1.09}$)	Potential Productivity Kg $ha^{-1}yr^{-1}$	Land Capability Class
		Slope	Soil Salinity	Soil Texture			
Foothills	425	0.6	1	1	420	978	6
	375	0.6	1	1	366	854	7
	425	1	1	1	733	1707	2
Valleys	375	1	1	1	639	1490	3
Possible Dryland Farming Areas	325	1	1	1	547	1274	4
	275	1	1	1	456	1062	5
Top and Middle of Alluvial Fans	325	0.85	1	1	458	1068	5
	275	0.85	1	0.94	357	832	7
	225	0.85	1	0.94	287	668	8
	175	0.95	1	0.94	246	574	8
Bottom of Alluvial Fans	175	1	1	1	370*	864	7
	125	1	1	1	257	599	8
Saline Alluvial Plain	175	1	0.72	1	195	454	9
	125	1	0.72	1	135	317	10
Sand Dunes	125	0.6	1	0.8	87	202	12
Dune Swales	125	1	1	0.97	187	435	9

* Rainfall plus water available from water table calulated from equation 2 in this case.

the relative low salinity. The total perennial cover of 11.4% is what could be expected in a zone of this rainfall (150 to 350 mm).

The relatively high lichen cover suggests that the effect of stock trampling on the cover is low and it affords a degree of soil protection. The biomass production has been measured between 380 to 400 kg ha^{-1} yr^{-1}, which is markedly lower than the potential production calculated in the range of 574 to 1068 (Table1.4). Hence, this land system is producing at about 50% of its ecological potential, which is probably due to the heavy spring and autumn grazing (Table1.1).

Bottom of Alluvial Fans: Most of this area is devoted to irrigation farming (Table1.1). It is a region of high productivity due to high ground water tables, found at depths of 0.5 to 3m. The ground water adds a calculated average of 250mm to the RAM relation. Salinity is moderate to low. These considerations mean that the moisture available for plant growth is in excess of that contributed by rainfall alone. This is reflected in the wide range of perennial species represented and their high cover of 71.0% found in the grassland grazing areas. The FBC of 0.78 suggests that there has not been a high invasion or increase of less-desirable and non-desirable species (Table1.3).

Measured biomass production is between 650 to1200 kg ha^{-1} yr^{1} compared to the calculated potential of 1137 to 1514. The area is very important to animal production as the crop residues produced are used for stock feed in the Autumn.

Saline Alluvial Plain: This is a shrubland of *Tamarix spp* with an understorey of *Reaumuria soongorica Maxim, Kalidium foliatum Moq* and *Nitraria sibirica Pall.* The composition of the association can differ widely depending on salinity, drainage and extent of flooding.

The perennial cover of 8.7% is probably as high as could be expected considering the rainfall of 125 to 175 mm and the high salinity. The high salinity results in a 23.3% cover of crusted salt. The IFC of 0.72 is lowered by the presence of non-palatable *Tamarix spp* and *Nitraria sibirica Pall.*

The measured range in biomass production of 750 to 950 kg ha^{-1} is higher than the calculated potential productivity of 317 to 454 kg ha^{-1} (Table1.4). The higher production is due to *Tamarix spp.* which extend their roots to a depth of 5 to 10 metres reaching the permanent ground water table, thus reducing the risk of a retardation of growth due to water stress.

Sand Dunes: The main perennial shrubland cover is *Haloxylon ammodendron Bge and H.persicum Bge.ex Boiss.* which have rooting depths of up to 10 metres, hence reaching the permanent ground water table. The total cover is relatively high for such a land system, possibly due to the fact that a) snow accumulates around the base of the plants, and on melting it increases the available moisture; b) the large area and limited availability of stock water in the spring, summer, autumn periods, results in a low stocking rate. Except for the dune crests, the IFC is also high, probably due to the low stocking pressure. The calculated potential production is 435 kg^{-1} yr^{-1} in the swales and 202 kg ha^{-1} yr^{1} on the dunes (Table1.4) compared to a measured 250 for the overall dune-swale system.

The dune crests are a very fragile area and all care must be taken to prevent overstocking and excessive fuel wood collection which could lead to dune mobilisation and sand movement onto the irrigation areas of the alluvial fans.

1.4 Results

Potential land capability:

Foothills: These lie in the 400 to 450 and 300 to 400 mm isohyte bands. Soil depths are >1m, salinities < 1.77mS, slopes are 17 to 25% and soil textures are clay loam to loam. This gives a RAM of 313 to 392 mm and a land capability class (LCC) of 6 to 7 (Figure1.4 and Table1.4). The deep soils are the result of loess deposition. The RAM is limited by the steeper slopes.

Top and Middle of Alluvial Fans: These lie in the isohyte ranges of 250 to 300 mm, 200 to 250 and 150 to 200 mm respectively (Figure1.4). Soil depths are > 1m, salinity 1.20 mS, slopes are 3 to 5% and 6 to 10%, and soil texture is sandy loam. This gives a RAM 269 to 335 mm and LCCs of 7 to 8. The deep soils are due to alluvial deposition.

Bottom of Alluvial Fans and Saline Alluvial Plain: These lie in the isohyte ranges of 100 to 150 mm and 150 to 200mm respectively. Soil depths are > 1m, slopes are 0-2%, salinities in the saline alluvial plain are 8.3 mS compared with 4.3 mS at the bottom of the alluvial fans. The soil texture is loam to clay loam. This gives RAMs of 135 to 195 and LCCs of 9 and 10 (Figure1.4 and Table1.4).

In the east and west of this region there are areas mainly used for irrigated agriculture (Figure1.4). In these areas the drainage lines supply ground water which increases the RAM (From equation 1.3) equivalent to 119 to 376 mm, which is additional water to support plant growth. Water is also pumped from the water table. The combined effect of these water sources is to increase the land capability class to an equivalent of 1.3 to 1.4.

The only known nutrient deficiency in the Fukang region is nitrogen. Because of the deep soils, where slopes are 0 to 2% land units with LCCs of 1 to 7 could be considered for irrigation when sufficient water of acceptable low salinity is available, or for dryland farming or grazing when additional water is not available. Those of LCCs 8 to 11 are suitable for forestry or any utilisation which ensures a continued perennial cover, such as conservative extensive grazing. Land with an LCC of 12, such as the sand dunes, have an absolute restriction to their utilisation due to their fragile nature. These dunes should be considered as conservation zones. The location and distribution of the land capability classes are shown in Figure 1.4.

The land of LCC 2 to 5 could be used for high productivity dryland farming or forage production, and are found in western and eastern valleys of the foothills (Fig.1.4).

1.5 Discussion

A comparison of the potential annual dry mass production (Y_{ep}) from the available moisture (equation 1.4) and the measured range in dry matter production (Table1.3) shows that :

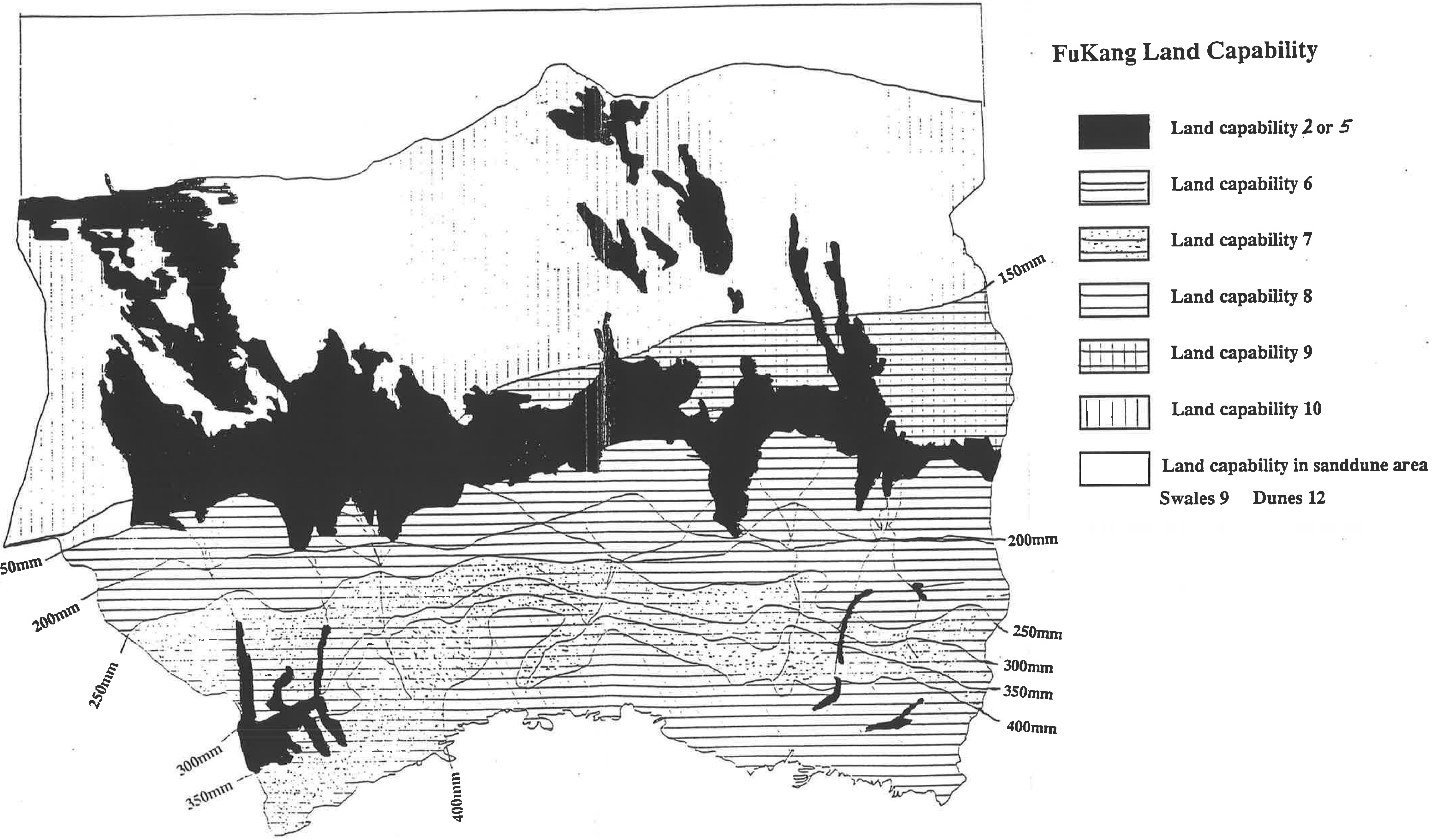


Fig 1.4 Fukang Land Capability Map

1. For the foothills there is a good correspondence considering that this region is heavily utilised (Table 1.1). A comparison suggests that it is producing at about 90% of its ecological potential.

2. In the top and middle of the alluvial fans the range of potential production is higher than the measured production (Tables1.4 and 1.3). However, this region is very heavily utilised (Table1.1) so such a discrepancy could be expected. A comparison of the potential production with the measured actual production suggests that the area is producing at about 50% of its ecological potential.

3. The bottom of the alluvial fans has a large variation in measured production, ranging from 650 to 1200 kg $ha^{-1}yr^{-1}$ (Table1.3). This is due to the high ground water tables and surface flow from the drainage lines (Figures1.1 and1.3) which contribute an additional 600 to 900 mm rainfall equivalent. (Jung 1990, personal communication).

   Where ground water is available, the potential production is 1137 to 1514 kg ha^{-1} $yr^{-1}$and where it is not, these levels are reduced to 600 to 864 kg $ha^{-1}yr^{-1}$. These correspond well to the measured range in production (Table1.3). Hence the region is producing at about 100% of its ecological potential.

4. For the saline alluvial plains the maximum measured range in production is higher than the calculated potential (Table1.3). This is due to the high production of non-palatable *Tamarix spp.* with roots reaching the ground water table. If the production of *Tamarix spp.* is subtracted from the measured biomass production, the annual biomass production is 400 to 250kg ha^{-1} which fits closely the calculated potential production (Table1.4).

5. For the sand dune areas, the calculated production is 202 and 435 kg

$ha^{-1}yr^{-1}$ for the swales (Table 4) compared to a measured overall (dunes plus swales) productivity of 250.

The above comparison between the calculated potential and measured actual production suggests that if account is taken of the increased production due to high water tables where they occur and lowered production due to heavy overgrazing, the methodology described gives a good indication of the lands productive potential. This means that the land capability classes defined by the methodology can be used in land use planning and management.

For example, in the top and middle alluvial region, the heavy overgrazing has resulted in a loss of about half of its potential productivity. This heavy grazing pressure is due to the high stocking rates and long grazing period (Table1.1). This might be rectified by the use of the valleys of high productive capability identified in the foothill region as fodder producing areas for lucerne *Medicago sativa L* and the high-producing grass species *Poa bulbosa Subsp L*, *Plantago minuta Pall* and *Kochia prostrata Schrad.* This fodder could be conserved and fed to supplement and ease the grazing pressure on the pastures of the alluvial fans.

The salinity of the alluvial plain reduces the potential productivity by about 30%. The nature of the salinity is complex. The salts identified are NaC1, $CaHC0_3$, Na_2C0_3, $CaC1_2$, $MgSO_4$, $MgC1_2$, Na_2SO_4. The descending order of toxicity to plants has been determined as Na_2C0_3, $MgC1_2$, NaC1, $CaC1_2$, $MgSO_4$, Na_2SO_4 (Gao and Zhou, 1990). High concentrations of Na_2C0_3 result in pH values for the soil of 9 to 10. The concentration of HCO_3^- and $C0_3^{2-}$ anions is highest at the higher altitudes, with SO_4^{2-} at mid-altitudes and $C1^-$ at the lowest altitudes. The growth of more palatable salt-tolerant plants (e.g., *Atriplex spp.*) should be researched along with *Camphorosma* *monspeliacia.*, *Cerathoides latens* and *Kochia prostrata*. Attempts should be made to reduce the salinity by improved drainage.

Drainage of the irrigation regions at the bottom of the alluvial fan area is also required to prevent further loss of productivity through salting. The drainage water could be used for fodder production of palatable salt-tolerant plants.

1.6 Conclusion

The primary annual net productivity calculated using parametric methods considerations gives reasonable agreement with measured values. However, it did show that this method can be used only in similar environments, provided data sets are available and complete. It also indicated that a more interactive way of dealing with the operative variables would be of great advantage.

APPENDIX 1

Weightings used in determining the Reflective Production Indicies:

1. Soil Depth

Soil Depth Interval(cm)	Relative Production Index
> 100	1.00
50 to 100	0.90
20 to 50	0.75
< 20	0.55

2. Slope

Slope (%)	Relative Production Index
0 to 2	1.00
2 to 5	0.95
5 to 10	0.85
> 10	0.80

3. Soil Texture

Soil Texture	Relative Production Index
Sands	0.80
Sand loams	0.97
Loams	0.94
Clay loams	1.00
Light clays	0.82
Medium/Heavy clays	0.68

4. Soil Salinity

Salinity (mS)	Relative Production Index
<8	1.00
8 to 16	0.72
16 to 24	0.48
< 24	0.24

Chapter 2. RANGELAND PRODUCTION -- Use of Models Incorporating Aggregated Knowledge and Fuzzy Construction

This chapter covers the use of fuzzy membership sets in which variables are scaled according to the way rainfall and soil variables affect the water available to promote plant growth and hence rangeland productivity. The fuzzy sets are constructed into an aggregated interaction matrix. This aggregation can be used to predict production.

2.1 Introduction

This work extends that presented in the review of Le Houerou (1984), which considered annual rainfall to be the major determinant of plant production in arid and semi-arid rangelands. Though soil variables, such as texture, slope and depth were considered important in plant production, they were not included in the methods of Le Houerou (1984) or Wisiol (1984).

The work covered here examines a different data set to that used by Le Houerou (1984) in that some information on soil variables is given together with that of annual rainfall and plant productivity. Rangeland data, as it covers large areas, tend to be crude in comparison to that available for agricultural production. Fuzzy techniques can deal with crude data, as well as data sets that remain incomplete and involve interactions which have not or cannot be related experimentally.

The work evaluates the use of a new technique that aggregates knowledge of the rainfall and soil variables that affect rangeland production. The method uses fuzzy sets (degrees of membership) which consider the way in which soil variables influence water availability to plants. The fuzzy sets were combined with weightings which reflect the importance of the interaction of the variables with respect to each other. These were aggregated in an interaction matrix of rainfall and soil variables. The matrix gives a weighted numeric summation of the variables scaled for their importance in determining rangeland production.

2.2 Method

Published data giving annual rainfall, aerial dry matter production (i.e. kg ha^{-1} yr^{-1}), soil texture, soil depth and slope were collected from the literature and are presented in Table 2.1. All results were from ungrazed experimental sites. Where soil depths are not given in Table 2.1 they were cited by the authors as being "deep" or "very deep".

A model was constructed in which the variables were aggregated into an interaction matrix. This matrix took into account the interplay of rainfall and soil variables in determining plant production. This was accomplished using fuzzy sets to determine the graded membership of variables combined with weightings for the importance of each variable with respect to each other in determining an outcome; water availablility to plants and hence rangeland productivity in the example considered here.

2.2.1 Interaction Matrix:

$$(W_{rf} \quad W_{s})\begin{pmatrix} D_{rf} \\ (W_{st} \quad W_{sd} \quad W_{ss})\begin{pmatrix} D_{st} \\ D_{sd} \\ D_{ss} \end{pmatrix} \end{pmatrix} = A^{*} \qquad (2.1)$$

Table 2.1 Annual rainfall, soil texture, slope, soil depth and annual above ground primary production in the rangelands of some arid and semi-arid zones of the world

Item	Location	Annual rainfall (mm)	Soil texture	Slope	*Soil depth	Annual primary production (kg DM/ha)	Reference
1	K.Wala (Pakistan)	149	Sandy loam	1-su		406	CH.M.Anwar Khan., 1971
2	FuKang County (China)	150	sandy	1-su		400	Zhu, J.Z.1984
3	Kinchega National Park Floodplain (Australia)	150	Clay sandy loam	Flat		630	Caughley et al., 1987
4	Kinchega National Park sandplain (Australia)	150	sandy clay loam	Flat		550	Caughley et al., 1987
5	Central Navajo (Arizona)	184	Loam fine sand	Gu		291	Harmon S.H., 1983
6	Central Navajo (Arizona)	184	Loam fine sand	1-su		409	Harmon S.H., 1983
7	Southwestern Hulunbuir Cleistogenes+stipa+agropyron (China)	200	Sandy loam	Gu		650	Hu, S.T, David.B &Harold W,1992
8	The Northern Tianshan area desert steppe (China)	200	Loam or sand clay loam	Flat		500	Hu, S.T, David.B &Harold W,1992
9	The Northern Tianshan area Carex+Artemisia (China)	200	Loamy sandy	Stp	<30cm (0.6)	450	Hu, S.T, David.B &Harold W,1992
10	The Northern Tianshan area Artemisia+stipa (China)	200	Silty loam	Flat		265	Hu, S.T, David.B &Harold W,1992
11	Kinchega National Park Floodplain (Australia)	200	Clay sandy loam	Flat			Caughley et al., 1987
12	Kinchega National Park sandplain (Australia)	200	sandy clay loam	Flat		645	Caughley et al., 1987
13	Northeastern Gansu Artemisia dalai-lamae Formation(China)	210	Silt loam	H		250	Hu, S.T, David.B &Harold W,1992
14	Santa Ana Mountains (California)	210	Sandy loam	u		359	Luebs,R.E. et al. 1971
15	Rough fescue-sedge (Australia)	236	Clay	Flat		374	Caughley et al., 1987
16	Southwestern Hulunbuir Stipa+bunchgrass (China)	250	Sandy loam	Su		675	Hu, S.T, David.B &Harold W,1992
17	Kinchega National Park Floodplain (Australia)	250	Clay sandy loam	Flat		886	Caughley et al., 1987
18	Kinchega National Park sandplain (Australia)	250	sandy clay loam	Flat		740	Caughley et al., 1987
19	Riverine plain and Barrer ranger (Australia)	250	clay or heavy clay	Flat		728	Caughley et al., 1987
20	FuKang County (China)	250	sandy loam	Gu		728	Zhu, J.Z.1984
21	K.Wala(Pakistan)	251	Sandy loam	1-su		726	CH.M.Anwar Khan., 1971
22	Tlats(SW Idaho)	251	Loam	1-su		800	Clayton.,et al., 1983
23	Chubara(Pakistan)	272	Sandy loam	1-su		868	CH.M.Anwar Khan., 1971
24	Gillette (Wyoming)	275	Clay	Gu		450	Frank.R.1980
25	Archer Substation (Cheyenne U.S.A)	289	Sandy loam	Gu		576	Frank Rauzi.,1979
26	Kinchega National Park Floodplain (Australia)	300	Clay sandy loam	Flat		1014	Caughley et al., 1987
27	Kinchega National Park sandplain (Australia)	300	sandy clay loam	Flat		835	Caughley et al., 1987
28	Dagar kotli(Pakistan)	300	Sandy loam	1-su		434	CH.M.Anwar Khan., 1971

Item	Location	Annual rainfall (mm)	Soil texture	Slope	*Soil depth	Annual primary production (kg DM/ha)	Reference	
29	Yan Chi County(China)	300	Sandy	Vgu		1035	Fu.J.H.,1983	
30	Yan Chi County(China)	300	Sandy loam	Vgu		900	Fu.J.H.,1983	
31	Yan Chi County(China)	300	Sandy loam	Vgu		570	Fu.J.H.,1983	
32	Nancy Gulch (SW Idaho)	302	Loam	Gu		770	Clayton.,et al., 1983	
33	Park Valley(Utah)	305	Clay loam	Vgu	25-60cm	1008	Michael H.el al., 1979	
34	East Idaho	305	Loam	1-su		905	Walter B.,1971	
35	Southeastern Wyoming(U.S.A)	319	Clay loam	1-su		803	Frank Rauzi,et al., 1983	
36	Sand dunes of Northern Ordos (China)	320	Sand	Su		1800	Hu, S.T, David.B &Harold W,1992	
37	Southeastern Wyoming(U.S.A)	324	Clay loam	1-su		848	Frank Rauzi,et al., 1983	
38	Tall grassland plateau stipa+leymus (China)	325	30-50cm bumurs	Gu		1500	Hu, S.T, David.B &Harold W,1992	
39	Tall grassland plateau stipa+cleistogenes (China)	325	Sandy loam	Gu		900	Hu, S.T, David.B &Harold W,1992	
40	Tall grassland plateau Artemisia frigida (China)	325	Sandy loam	H		600	Hu, S.T, David.B &Harold W,1992	
41	Tall grassland plateau Leymus+herbs (China)	325	Sandy loam	U		987	Anon.,1964	
42	Tall grassland plateau Leymus+stipa (China)	325	Loam	Plain		1023	Anon.,1964	
43	Tall grassland plateau Bunch grasses (China)	325	Sand	U		404	Anon.,1964	
44	Tall grassland plateau Shrubs+grasses (China)	325	Sand	U		488	Anon.,1964	
45	Sidney (Montana)	326	Fine loamy sand	1-su		788	Ross Wight,J. et al. 1979	
46	Sidney (Montana)	330	Fine loamy sand	1-su		720	Ross Wight,J. et al. 1979	
47	Hills and Gullied area of loess plateau(china)	331	Silt loam	Vgu		1030	Zou,H.Y. et al.,1980	
48	Sidney (Montana)	342	Fine loamy sand	1-su		1205	Ross Wight,J. et al. 1979	
49	Southeastern Wyoming(U.S.A)	343	Clay loam	1-su		759	Frank Rauzi,et al., 1983	
50	Lower Sheep Greek (SW Idaho)	347	Loam	U		680	Clayton.,et al., 1983	Gravelly (A)
51	Xi Liao River Grassland(China)	350	sand	U		700	Hu, S.T, David.B &Harold W,1992	

Item	Location	Annual rainfall (mm)	Soil texture	Slope	*Soil depth	Annual primary production (kg DM/ha)	Reference
52	Western foothill of the great Khingan(china)	350	Loam	Uh		1250	Hu, S.T, David.B &Harold W,1992
53	The outer Tibetan Steppe meadow (China)	350	Sandy loam	Uh		1125	Hu, S.T, David.B &Harold W,1992
54	Southeastern Wyoming(U.S.A)	351	Clay loam	1-su		760	Frank Rauzi,et al., 1983
55	Dagar kotli(Pakistan)	355	Sandy loam	1-su		1242	CH.M.Anwar Khan., 1971
56	Sagebrush flat(North Dakota)	350	Silty loam	1-su		2268	Michael, D. et al.1986
57	East Tracy Mountain(North Dakota)	350	Silty	1-su		2338	Michael, D. et al.1986
58	West Tracy Mountain(North Dakota)	350	Sandy loam	1-su		1387	Michael, D. et al.1986
59	Upland(North Dakota)	350	Loam	1-su		1637	Michael, D. et al.1986
60	Harper county (Oklahoma U.S.A)	360	Loam	Gu		1310	William, et al.,1984
61	Central Navajo (Arizona)	360	SIlt loam	1-su		1945	Harmons Hodgkimson., 1983
62	Sidney (Montana)	368	Fine loamy sand	1-su		1321	Ross Wight,J.et al. 1979
63	Ascalon loam(Wyoming range Site)	370	Loam	1-su		1100	Hart.R.H. et al.1985
64	Altan loam(Wyoming range Site)	370	Loam	Vgu		930	Hart.R.H. et al.1985
65	Cascajo loam(Wyoming range Site)	370	Loam	Gu	Shallow	890	Hart.R.H. et al.1985
66	Larim variant loam(Wyoming range Site)	370	Loam	Gu	Shallow	840	Hart.R.H. et al.1985
67	Sidney (Montana)	376	Fine loamy sand	1-su		1100	Ross Wight,J.et al. 1979
68	Sidney (Montana)	377	Fine loamy sand	1-su		1276	Ross Wight,J.et al. 1979
69	Sidney (Montana)	394	Fine loamy sand	1-su		933	Ross Wight,J.et al. 1979
70	Southern great khingan hill grass land(China)	400	Loam or clay loam	H		1750	Hu, S.T, David.B &Harold W,1992
71	Eastern part of loess plateau(China)	400	Sandy loam	Uh		1500	Hu, S.T, David.B &Harold W,1992
72	East Idaho	406	Loam	1-su		1387	Walter B.,1971
73	Santa Ana Mountains (California)	420	Sandy loam	U		1279	Luebs,R.E. et al. 1971
74	Santa Ana Mountains (California)	420	Sandy loam	Gu		1728	Luebs,R.E. et al. 1971

Item	Location	Annual rainfall (mm)	Soil texture	Slope	*Soil depth	Annual primary production (kg DM/ha)	Reference	
75	Santa Ana Mountains (California)	420	Sandy loam	Swale		2603	Luebs,R.E. et al. 1971	
76	Northern Hulunbuir (China)	424	Clay loam	U		1250	Hu, S.T, David.B &Harold W,1992	
77	Sidney (Montana)	424	Fine loamy sand	1-su		763	Ross Wight, J. et al. 1979	
78	FuKang County (China)	425	Loam or clay loam	Uh		903	Zhu, J.Z.1984	
79	Harper county (Oklahoma U.S.A)	430	Loam	Gu		1510	William, et al.,1984	
80	Southern edge of the Rio Grande plain (Texas)	430	Sandy loam	1-su		1689	Conzalez, C.L. et al. 1979	
81	Southeastern Wyoming(U.S.A)	440	Clay loam	1-su		1087	Frank Rauzi,et al., 1983	
82	Mali,South Sahel	449	sand	Su		1875	De Vries, Penning et al., 1982	
83	Mali,South Sahel	449	Silty	Su		1975	De Vries, Penning et al., 1982	
84	Central great khingan shrub grassland (china)	450	Loam or clay loam	Stp		1000	Hu, S.T, David.B &Harold W,1992	
85	Central great khingan meadow grassland (china)	450	Loam or clay loam	Flat		2000	Hu, S.T, David.B &Harold W,1992	
86	Central great khingan wet meadow grassland (china)	450	Loam or clay loam	Gu		2000	Hu, S.T, David.B &Harold W,1992	
87	South of Xilinggol(China)	450	30-50cm humurs	Gu		2500	Hu, S.T, David.B &Harold W,1992	
88	North Dakota	453	Silty loam	Flat	Shallow	2480	Hofmann,L.et al.1989	
89	Big Spring(Texas)	468	Deep sand	1-su		925	Koshi,P.T. et al,. 1981	
90	Nettleton (SW Idaho)	483	Loam	H		1150	Clayton.,et al., 1983	Rock stone(B)
91	Harper county (Oklahoma U.S.A)	490	Loam	Gu		1885	William, et al.,1984	
92	Sidney (Montana)	493	Fine loamy sand	1-su		1215	Ross Wight, J. et al. 1979	
93	Upper Sheep Greek (South face)(SW Idaho)	508	loam	H		620	Clayton.,et al., 1983	Rocky(C)
94	Upper Sheep Greek (North face)(SW Idaho)	508	loam	H		1970	Clayton.,et al., 1983	
95	Alberta Rough fescue (U.S.A)	516	Loam fine sandy	1-su		2360	Michael, W. 1992	
96	Alberta Rough fescue+ idaho fescue (U.S.A)	516	Loam fine sandy	Gu		1872	Michael, W. 1992	
97	Alberta Parry oatgrass+Rough fescue (U.S.A)	516	Sandy loam	H		1523	Michael, W. 1992	

Item	Location	Annual rainfall (mm)	Soil texture	Slope	*Soil depth	Annual primary production (kg DM/ha)	Reference	
98	Alberta Rough fescue +sedge(U.S.A)	516	Loam	Vgu		2000	Michael, W. 1992	
99	Alberta Kentuky bluegrass+Rough fescue (U.S.A)	516	Fine sandy	Gu		1972	Michael, W. 1992	
100	Sidney (Montana)	527	Fine loamy sand	1-su		1245	Ross Wight,J.et al. 1979	
101	Debrecen plot 1. (Hungary)	539	Loam or clay loam	Flat		4260	Sophia Toth.,1989	
102	Debrecen plot 2. (Hungary)	539	Sandy loam	Flat		3590	Sophia Toth.,1989	
103	Debrecen plot 3. (Hungary)	539	Loam sand	Flat		2400	Sophia Toth.,1989	
104	Debrecen plot 4. (Hungary)	539	Loam sand	Flat		2860	Sophia Toth.,1989	
105	Debrecen plot 5. (Hungary)	539	Clay	Flat		3350	Sophia Toth.,1989	
106	Debrecen plot 6. (Hungary)	539	Clay	Flat		4430	Sophia Toth.,1989	
107	East Idaho	559	Loam	1-su		2464	Walter B.,1971	
108	North Texas	559	Clay loam	Gu		2550	Scifres, C.J.et al. 1971	
109	Harper county (Oklahoma U.S.A)	560	Loam	Vgu		1160	William, et al.,1984	Coarse silty (D)
110	Santa Ana Mountains (California)	589	clay loam	Swale		4914	Luebs, R.E. et al. 1971	
111	Yellow river delta (China)	601	Silt loam	Flat		5000	Hu, S.T, David.B &Harold W,1992	
112	Eastern Utah	610	Loam or clay loam	Stp		1837	Laycock, W.A. et al. 1981	
113	Texas A&M Uni Agri Research Station	610	Clay	Vgu		3446	Bryant, F.C. et al., 1981	
114	Harper county (Oklahoma U.S.A)	670	Loam	Gu		1780	William, et al.,1984	Coarse silty (E)
115	Whiskey Hill (SW Idaho)	701	Sandy loam	U		1360	Clayton.,et al., 1983	Corase(F)

* Where soil depths are not given it was mentioned in the articles that the soils were deep or very deep, hence >60cm deep and given a graded membership of 1. Points A, B, C, D, E and F are soil constraints.

The linear form of the interaction matrix, equation (2.1), is:

$$A^* = W_{rf} D_{rf} + W_s (W_{st} D_{st} + W_{sd} D_{sd} + W_{ss} D_{ss}).$$

Where D_{rf} = Graded membership for rainfall.

D_{st} = Graded membership for soil texture.

D_{sd} = Graded membership for soil depth.

D_{ss} = Graded membership for soil slope.

W_{st}, W_{sd} And W_{ss} are weightings for soil texture, soil depth and soil slope respectively. The sum of these weightings must equal to one (Zadeh, 1965).

W_{rf} and W_s are comprehensive rainfall and soil weightings reflecting the relative importance of rainfall and soil variables to each other in determining productivity. The sum of these must also equal to one.

A* is the Aggregated Weighted Index of the rainfall and soil variables (Aggregated Soil Moisture Index ASMI) determining biomass productivity.

Adjustments can be made to A* for conditions that either increase or decrease production by the relation:

$$A = A^* \prod_{i=1}^{n} Ci \prod_{i=1}^{n} Si \qquad (2.2)$$

Where $\prod_{i=1}^{n} Ci$ = product of the climatic variables and $\prod_{i=1}^{n} Si$ = product of the soil conditions that decrease or increase production.

In this case, Liebig's law of minimum was used where the most limiting variable determines the level of productivity.

2.2.2 Graded Membership

The Graded Membership Function expresses inexactness into a formal optimising procedure. It represents knowledge of how a variable affects a process. Coefficients are represented by interval rather than exact values to give an estimate of the degree of membership that a variable has to a particular characteristic.

The degree of graded membership has been defined by Zadeh (1983). Let *C* be a set and *c* a member of that set. A fuzzy subset *F* of *c* is defined by a membership function *u* that measures the degree to which *c* belongs to *F*.

An example of a graded membership *u* of a considered variable (x) is,

$$u(x) = \begin{cases} 0 & x \leq v_1, \\ 1 - \dfrac{v_2 - x}{v_2 - v_1} & v_1 < x \leq v_2, \\ \dfrac{v_3 - x}{v_3 - v_2} & v_2 < x \leq v_3, \\ 0 & x > v_3. \end{cases} \qquad (2.3)$$

Where $u(x)$ = degree of graded membership of x

v_1 = minimum value for which membership is valid.

v_2 = the optimal value for membership.

v_3 = the upper limit for membership.

x = measured value.

The Graded Membership Function can be represented in different forms according to the type of function represented. This depends on the concept of how one variable belongs to another. In constructing the following Graded Membership Functions universal rules known to govern biomass production in arid and semi-arid were used.

2.2.3 Degree of Graded Membership

The construction of the Graded Membership Function, values used and reasons for their choice are described as follows:

Variable	Membership Function	Rules	Reasons for Choice
Annual Rainfall x_1(mm)	$u(x_1) = \frac{x_1}{700}$	$0 < x_1 \leq 700$	A rainfall of 700 mm is considered the upper limit for the semi-arid zone -- FAO classification
	1	$x_1 > 700$	
Soil Slope x_2 (%)	$u(x_2) =$ 1.0	•0-3% or Level to slightly undulating (L--Su).	To account for the effect of slope on run off (Walker.1983)
	0.95	•3-5% or Very gently undulating (Vgu).	
	0.90	•5-10% or Gently undulating (gu).	
	0.85	•10-20% or Undulating (u).	
	0.80	•20-30% or Undulating to hill (uh).	
	0.70	•Hilly (h).	
	0.60	•Steep (Stp).	

Soil Depth
x_3 (cm)

$$u(x_3)=\begin{cases}0.6 & x_3 < 25\\ 0.8 & 25 \le x_3 < 60\\ 1.0 & x_3 \ge 60\end{cases}$$

To account for the effect of soil depth on water holding capacity and root growth.

Soil texture
x_4

$$u(x_4)=\begin{cases}0.32 & \text{Sand}\\ 0.32 & \text{Loamy sand}\\ 0.58 & \text{Sand loamy}\\ 0.74 & \text{Loam}\\ 0.95 & \text{Silt loam}\\ 1 & \text{Silt}\\ 0.79 & \text{Sandy clay loam}\\ 0.74 & \text{Clay loam}\\ 0.79 & \text{Silty clay loam}\\ 0.53 & \text{Sandy clay}\\ 0.68 & \text{Silty clay}\\ 0.68 & \text{Clay}\end{cases}$$

To account for the effect of soil texture on water holding capacity.
(Thomas&Squires 1991)

2.2.4 Weighting Determination

Weightings give the importance of the variables with respect to each other in determining an overall outcome. They are given in the range 0.0 to 1.0 according to their assessed importance in bringing about the result (Zadeh ,1967). Weightings were obtained from a least squares analysis of the data presented in Table 2.1.

From the biomass against rainfall data in Fig 2.1& 2.2, the equation of biomass against rainfall is was derived.

$$Y = a\,10^{bRf}, \qquad (2.4)$$

where Y = Dry matter production

Rf = annual rainfall

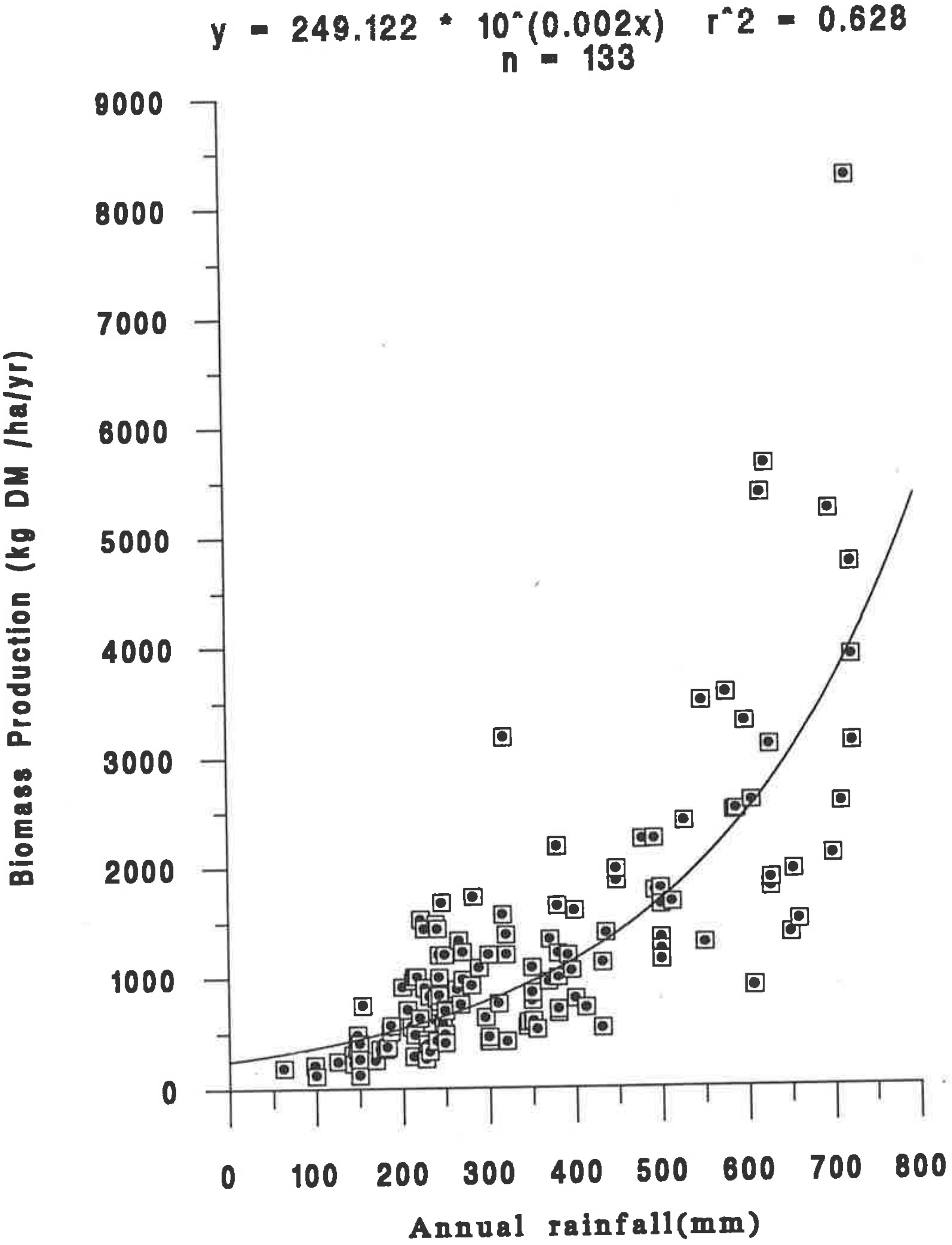


Fig 2.1 The relationship between annual rainfall and biomass production from the data presented by Le Houerou (1984)

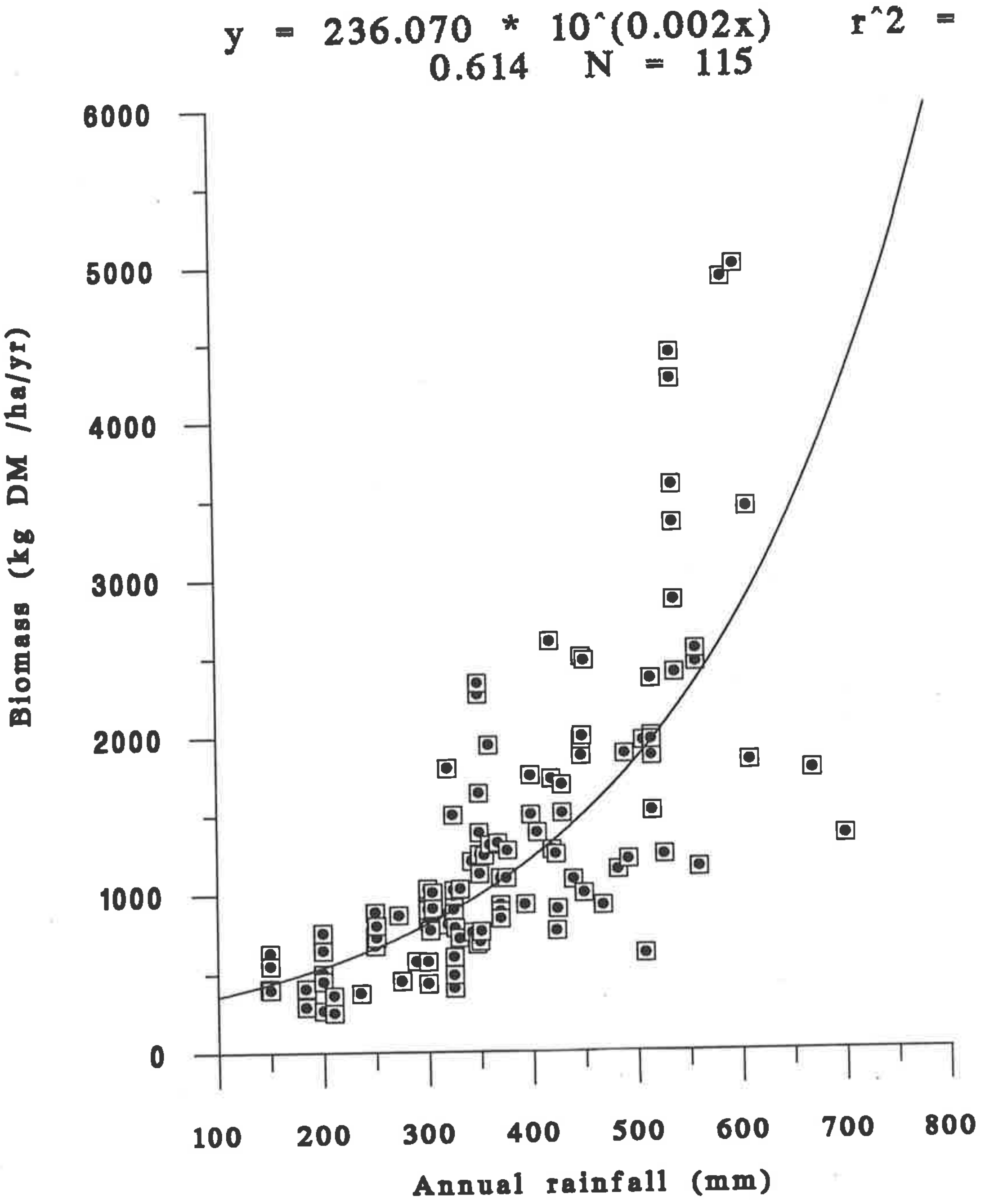


Fig 2.2 Annual rainfall against biomass from the data given in Table 2.1.

If we consider the soil variables also, the equation is:

$$Y = a\ 10^{\,bA^*}, \qquad (2.5)$$

where $A^* = W_{rf}\,D_{rf} + W_s\,(\,W_{st}\,D_{st} + W_{sd}\,D_{sd} + W_{ss}\,D_{ss}\,)$. This is the linear form of the interaction matrix (equation 2.1) which considers both rainfall and soil variables.

Using the degrees of membership and the yields of the 115 data points given in Table2.1, the equation was solved for the weightings using the least squares method,

$$\text{Min } Q = \sum_{i=1}^{n}\left(\lg Y_i - \lg \hat{Y}_i\right)^2, \qquad (2.6)$$

where Q is sum of the obtained biomass production minus the predicted production squared, Yi is actual biomass production, and $\hat{Y}i$ is the calculated production.

2.3 Comparison of Methods

The fuzzy method developed here was compared to a parametric model described by Steeley *et al.* (1984). The model took into consideration rainfall, slope, soil salinity and depth in to a multiplicative way;

$$Y_{ep} = 2.33[Rf\,(\,S_{sl}\ \ S_{sal}\ \ S_d\,)]^{1.09}, \qquad (2.7)$$

where Y_{ep} = Annual production of ecological potential (kg/ha/year)

R_f = Annual rainfall (mm)

S_{sl} = Slope (%)

S_{sal} = Soil salinity (mS)

S_d = Soil depth (cm)

The weightings for these variables are given in Steeley et al (1984). Rf (S_{sl} S_{sal} S_d) is termed the relative available soil moisture index (RAM).

2.4 Results

2.4.1 Rainfall, biomass production relations

Fig 2.1 shows the relation between annual rainfall and dry matter production from the results given by Le Houerou (1984). The relation of the curve of best fit is:

$$Y = 249 \times 10^{0.002Rf} \qquad R^2 = 0.63 \qquad (2.8)$$

where Y = Yield in kg/dry matter/ ha/year

Rf= Annual rainfall in mm

The annual rainfall production results given in Table 2.1 are shown in Fig 2.2. The relation of the curve is

$$Y = 236 \times 10^{0.002Rf} \qquad R^2 = 0.61 \qquad (2.9)$$

where the symbols have the same meaning as in equation 2.8 above. The similarity in the two different data sets is remarkable. The explanatory values (R^2) are similar, 0.63 and 0.61, respectively.

This gives confidence in assuming 60% of the variability in annual production of arid and semi-arid regions is due to variations in the rainfall. Similar results have been found for agricultural crops in semi-arid regions, such as wheat (French and Schultz

1984 and Sun and Thomas 1993a) and field peas (Sun and Thomas 1993b), where 60% of the variability in production is determined by the annual rainfall. The remaining 40% of the variability is governed mainly by soil variables.

2.4.2 Rainfall Use Efficiency

Le Houerou (1984) coined the term of Rainfall Use Efficiency (RUE) which was defined as the number of kilograms aerial dry matter phytomass produced over one hectare in one year per millimeter of total rainfall. The RUE over intervals of 100 mm rainfall from the results given in Fig 2.2 are shown in Table 2.2. These are very similar to those found by Le Houerou. The RUE tends to decrease with increasing aridity as evapotranspiration increases.

Table 2.2. Rainfall Use Efficiency over various rainfall ranges

Rainfall Range (mm)	RUE (kg DM/ha/yr/mm)
100-200	2.33
200-300	2.60
300-400	2.86
400-500	3.44
500-600	4.30
600-700	5.18
700-800	6.93

Considering the wide range of ecosystems covered throughout the world (Table 2.1) there is a universality in the RUE. However there could be considerable local variations due to slope, soil texture, aspect, rainfall intensity, vegetation type, extent of utilization and structure (Le Houerou 1984, Wisiol 1984, Thomas & Squires 1991). The seasonality of the rainfall, winter or summer, does not make any appreciable difference to the RUE.

2.4.3. Parametric Model

Fig 2.3 shows the plot of the yield data against the RAM relation calculated for the soil variables from the data given in Table2.1. This gives an explanation of variability (R^2) of 0.67 which does not significantly improve the predicability in comparison to relations (8) and (9), which consider annual rainfall only. The parametric relation does not take into consideration the interaction of the variables considered.

2.4.4 Aggregated soil moisture index (ASMI) relations

The ASMI calculated using relation 2.1 (ie A*) plotted against yield from the data given in Table 2.1, is shown in Fig 2.4. This increases the explanation of variance (R^2) to 0.74. The data covered the rainfall range of 149 to 701 mm. On examination of the data it was found that out-rider points marked in table 2.1 and fig 2.4 were coarse sands. Coarse sands have a high suction and hence a low hydraulic conductivity. As a consequence these wet slowly as movement through the soil is mainly by matric forces. This would be a constraint to plant roots obtaining water. To account for this equation 2.2 was used. A constraint of 0.8 was applied to the soil constraint factor. The results are shown in Fig 2.5. The equation of best fit curve is

$$Y = 29.6 \times 10^{2.39A^*} \qquad R^2 = 0.81 \qquad (2.10)$$

The explanation of variance of 0.81, will make this a very useful relation in determining rangeland biomass production.

Table 2.3 gives the least square adjusted weightings for the rainfall and soil variables. These are given for the lower (149 to 350 mm), higher (351 to 701 mm) and the total (149 to 701mm) range of the rainfall presented in Fig 2.5.

Table 2.3 Weightings for rainfall, soil texture, slope and depth found using the least square adjustment method.

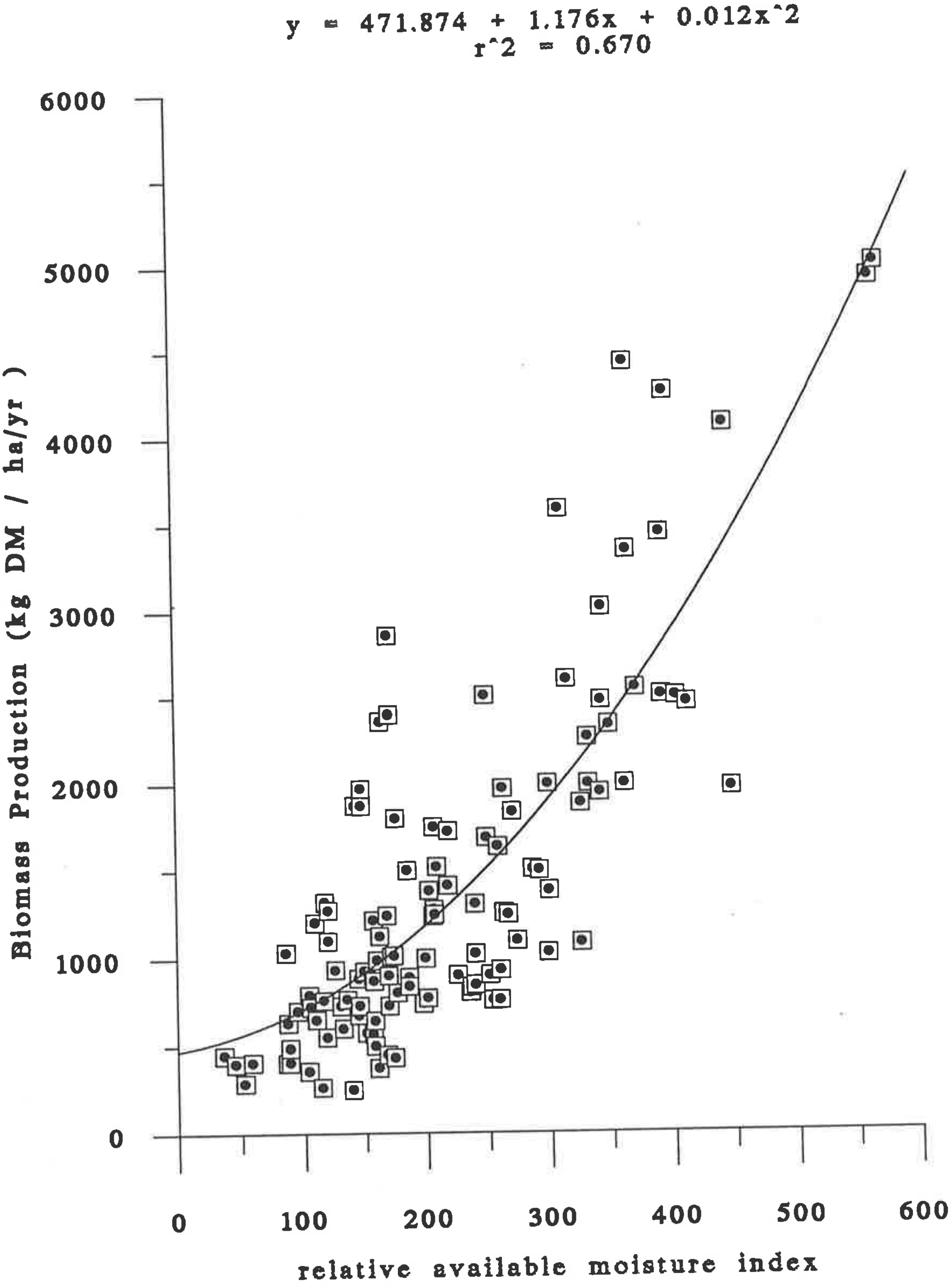


Fig 2.3 Biomass production against the relative available moisture index

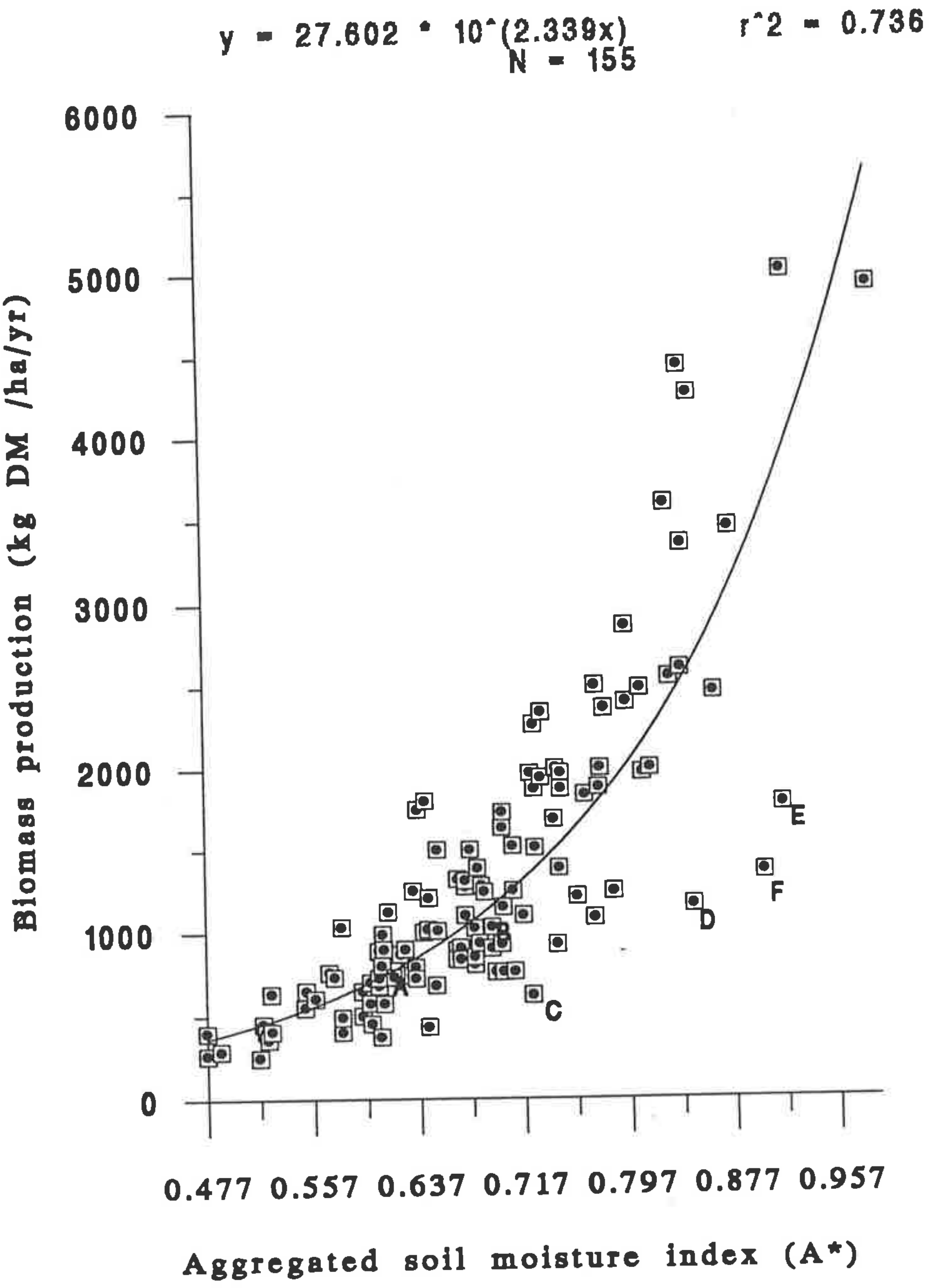


Fig 2.4 Biomass production against the Aggregated soil moisture index before consideration for soil constraints. Points A, B, C, D, E and F are coarse sands(table 2.1)

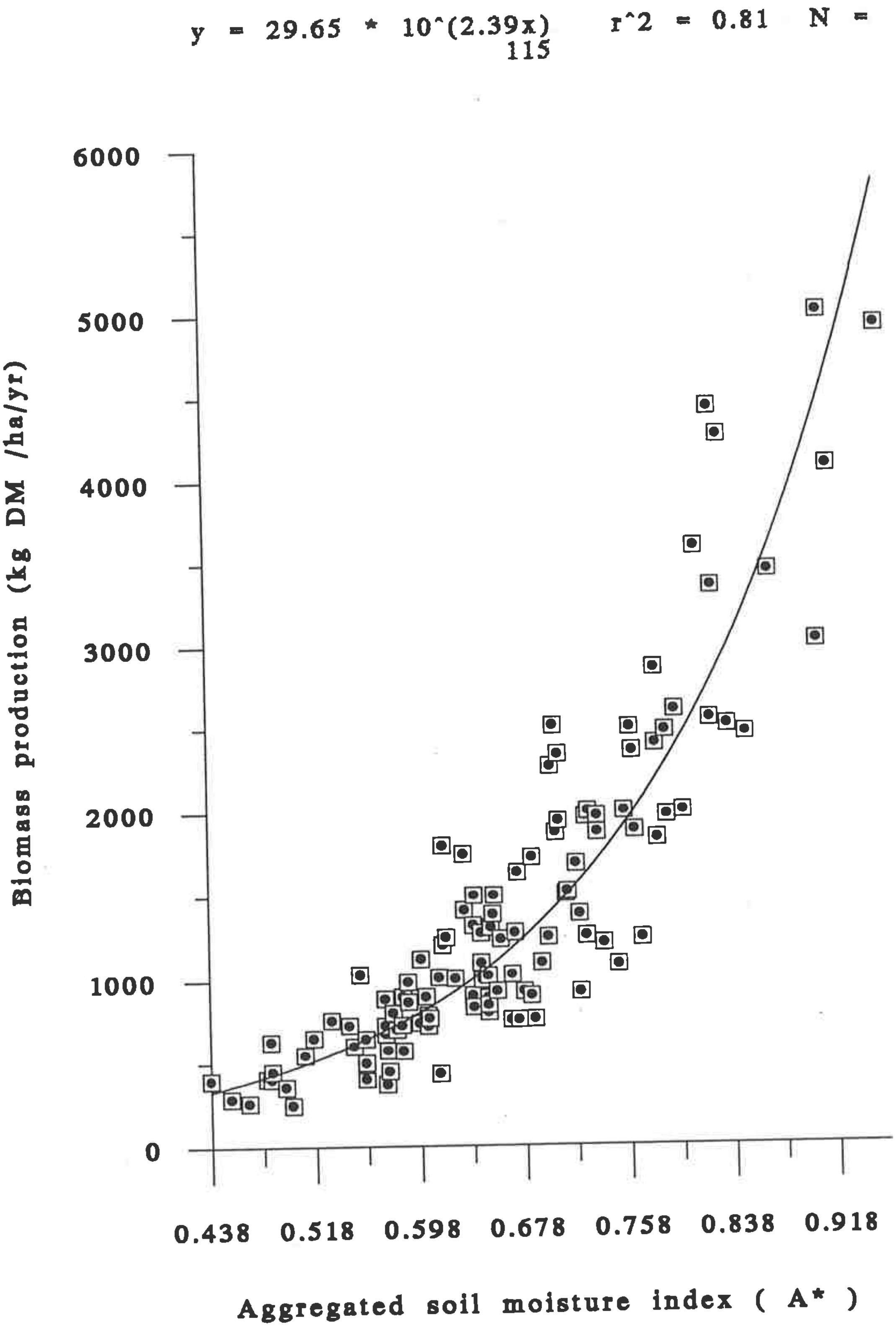


Fig 2.5 Biomass production against the aggregated soil moisture index after consideration for soil constraints

Variable	Rainfall Range (mm)		
	149-350	351-701	149-701
Rainfall	0.62	0.46	0.59
Soil Texture	0.08	0.14	0.12
Slope	0.33	0.22	0.23
Depth	-0.03	0.18	0.06
Number of data points	53	62	115
R^2	0.56	0.68	0.81

Attention is drawn specifically to the following:

(1) Rainfall: This is weighted higher in the lower rainfall range. This would be expected.

(2) Soil texture: Weightings remain fairly constant. This was not expected. It was thought that the higher rainfall acceptance of sandy soils would be of importance in the lower rainfall range, however, the rainfall range only goes as low as 149 mm, at lower rainfalls soil texture and rainfall acceptance could become important.

(3) Soil slope: This was weighted the hightest of soil variables throughout the rainfall ranges considered, especially at lower rainfalls. It seems that run-off and drainage play important roles in controlling productivity. Certainly the run-on from slopes to flat areas plays an important role in increasing productivity.

(4) Depth: The weightings given for depth certainly reflect field data. At lower rainfalls, soil depth is of no importance. This is understandable because a soil depth ≥

10 cm would normally be adequate to store all the water falling at rainfall < 350 mm. Conversely, the weighting increases at higher rainfall where water storage would become significant.

2.5 Discussion

The results show that combining rainfall and soil variables in an interactive way, which considers the interplay of how they affect water availability to plants, gives a model of better predictive value than those that consider annual rainfall alone or a parametric model that does not consider the interactions of the variables.

An accurate method of predicting rangeland production is very important in grazing management. The range manager has to adjust stocking rates over large areas where production varies in space and time. Accurate adjustment of stocking rates in relation to productivity is essential to sustainable rangeland use.

The methodology described here has increased the predictability of rangeland production by 15% to 20%. This could be further increased if finer-grained data was available, such as. effective growing season rainfall (Thomas and Morris 1972, Reid and Thomas 1973). However, rangelands data are characteristically coarse.

The aggregated soil moisture index (A*), gives a measure of land capability for plant production. This is important as many rangelands are so badly degraded that the land capability cannot be judged on the existing vegetative cover. Knowing land capability is important when considering land most suitable for regeneration. It is most economic to regenerate land of the highest potential production capability first (Thomas et al.1986).

Where no empirical knowledge is available, weightings can be obtained from local pastoralists and experts. This is described in chapter 3. Land users and local experts are asked the importance of the variables considered. For example, they are asked what they consider from their experience are the "least important", "marginally important", "important", "very important" and "most important" factors in determining production. From their answers, weightings can be derived (see Introduction IV.III).

Relation 2.2 is very useful in adjusting for factors that could either decrease or increase production. Relations that could be used to adjust for (1) the effect of vegetative on rainfall retention (2) the effect of soil erosion, and (3) ground cover, in relation to productivity, have been presented in Thomas and Squires (1991). Examples of factors that decrease productions are: (1) exceptionally hot or cold conditions during the effective growing season; (2) late snow melt; (3) the effect of fire; (4) grazing by native or feral animals; (5) composition of the vegetation eg. proportion of edible and inedible plants; and (6) nutritive value of the vegetation. Examples of factors that could increase productivity are: (1) water run on or discharge areas where there is an increase in water deposition; (2) water retention works; (3) fertilizer application; (4) destocking; (5) weed control; and (6) seeding. The effects that these could have on increasing production have been modelled by Thomas et al.(1986).

The use of fuzzy techniques in an aggregated knowledge methodology is important as it gives us a computational framework for dealing with: (1) complex interactions which have not or cannot be related experimentally; (2) data sets that always remain incomplete; and (3) data which incorporates expert and user knowledge.

Chapter 3. Analysis of Wheat Yields
Use of Models Incorporating Aggregated Knowledge and Fuzzy Membership Construction

In chapter 2, a method was developed using fuzzy membership functions to construct an aggregated interaction matrix to predict rangeland production. As the data set was large, weightings could be derived using a least squares analysis. This chapter compares the use of expert/user weightings with those derived by a least squares analysis in an aggregated knowledge model to predict wheat yield. The results show that expert knowledge can be satisfactorily used to estimate yields. This is considered important as it gives means of estimating crop yields when data is limited.

3.1 Introduction

This work explores the use of a new techniqe that aggregates knowledge of the climate and soil variables that affect wheat production to analyse and predict grain yield. The method uses Fuzzy membership construction.

The analysis of wheat yields in South Australia has been the subject of considerable study (Cornish, 1950; Greacen and Hignett, 1976; French and Schultz, 1984). Hence, an analysis of wheat yields provides a good basis for testing the new aggregated knowledge method.

The knowledge aggregation is done in an interaction matrix of climate and soil variables. The matrix is a weighted summation of variables scaled for their importance in determining crop yield. These are aggregated to give an integrated value. Weights were obtained in two ways: (1) from user/expert estimates of the importance of the considered variables in determining yield, and (2) a least squares analysis. The aggregation was done by grouping the knowledge of the variable into graded membership values in fuzzy sets. The values obtained from the fuzzy sets were weighted according to the user/expert assessment of their importance in determining yield. The membership values for the variables, together with their weights are combined in an interaction matrix. The matrix gives a summation of the membership of the variables, scaled for their importance in determining yield, and aggregates them into integrated numeric values. These values were correlated with yields.

Previous models were based on growing season rainfall or crop water use. The rationale being that plant yield and transpiration (use of available water) are directly linked. The higher the stomatal conductance the greater the CO_2 uptake and hence water vapour loss. These models can explain around 60% - 70% of the variation in yield. In this study, the known soil characteristics which affect yield are also considered. The object was to: 1) increase our knowledge of the interplay of climatic and soil factors in determining yield, and 2) give a basis for land evaluation for growing wheat in autumn sowings.

Many crop physiological models have been constructed to predict crop production. These are very data intensive and require a high degree of instrumentation. In many practical circumstances it is often difficult to obtain even reliable rainfall data. Multiple regression models have also been used to predict yield. However, such models are specific to a given region and cannot be universally applied. The development of the aggregated knowledge methodology may provide an alternative solution.

3.2 Method

Data was collected from the South Australian Department of Agriculture's Field Crop Evaluation Reports for wheat variety trials. These were conducted at sites throughout the wheat growing area of South Australia. The trials included 22 wheat varieties. Data used are obtained during the 1989, 1990 and 1991 growing seasons. The data available consisted of yields, monthly rainfall, soil texture and pH (Table 3.1).

The climate is Mediterranean, with 70% - 80% of the rainfall occurring in the April to October (winter) growing season. During this season the mean maximum temperatures range from 16°C - 20°C and the mean minimum from 6°C - 10°C.

Models were constructed relating yields to growing season rainfall. These were compared to knowledge-based models using the following interaction matrix, which took into account the interplay of climatic and soil variables.

3.2.1 General Relationships

- **Interaction matrix**

$$\begin{pmatrix} W_c & W_s \end{pmatrix} \begin{pmatrix} \begin{pmatrix} W_{rf} & W_t & W_l \end{pmatrix} \begin{pmatrix} D_{rf} \\ D_t \\ D_l \end{pmatrix} \\ \\ \begin{pmatrix} W_{st} & W_{sd} & W_{pH} & W_{sl} & W_{ss} \end{pmatrix} \begin{pmatrix} D_{st} \\ D_{sd} \\ D_{pH} \\ D_{sl} \\ D_{ss} \end{pmatrix} \end{pmatrix} = A^* \qquad (3.1)$$

The linear form of the interaction matrix is,

$$A^* = Wc\,(W_{rf} D_{rf} + W_t D_t + W_l D_l) + Ws\,(W_{st} D_{st} + W_{sd} D_{sd} + W_{pH} D_{pH} + W_{sl} D_{sl} + W_{ss} D_{ss})$$

Where:

Table 3.1 Sites,Seasonal rainfall,soil pH and texture data used in the calculation of the aggregated weighted index,A*

Site and year	**Yield(t/h)**	**Seasonal RF(mm)**	**Soil pH**	**Soil texture**	**A***
Warramboo 1991	1.459	241.0	8.5	sandy clay loam	0.663
Ungarrra(A)* 1991	2.922	316.0	6.5	sandy loam	0.787
Streak Bay 1991	2.300	289.0	8.5	sandy loam	0.707
Penong 1991	1.740	202.3	8.1	sandy clay loam	0.678
Nunjikompita 1991	2.028	263.5	8.5	sandy loam	0.687
Mitchellville1991	1.235	168.4	8.3	sandy clay loam	0.629
Minnpa 1991	2.305	292.2	8.5	sandy clay loam	0.701
Kimba 1991	1.398	219.0	8.5	sandy clay loam	0.646
Kalanbi 1991	1.263	197.3	8.5	sandy clay loam	0.630
Mintaro 1991	5.565	458.3	6.7	clay loam	0.846
Spalding(B)* 1991	5.384	329.0	6.5	sand loam	0.796
Turretfield 1991	4.123	378.0	7.3	clay loam	0.785
Urania 1991	2.936	343.6	8.5	sandy clay loam	0.736
wokurna 1991	3.143	225.0	7.1	sandy clay loam	0.707
Cummins 1990	2.968	340.6	7.5	clay	0.754
Kalanbl 1990	1.317	212.3	8.5	sandy clay loam	0.641
Kimba 1990	1.070	224.7	8.5	clay loam	0.611
Lock 1990	2.150	243.4	8.0	clay loam	0.683
Minnipa 1990	1.927	252.6	8.5	sandy clay loam	0.670
Mitchellville1990	1.064	221.0	9.0	sandy clay loam	0.584
Nunjikompita 1990	1.780	267.0	8.6	sandy loam	0.678
SteakyBay(C)*1990	1.305	273.5	8.5	sandy clay loam	0.695
Ungarra 1990	2.800	360.0	6.0	loamy sand	0.718
Warramboo 1990	1.537	228.0	8.5	sandy clay loam	0.653
Cummins 1989	3.238	325.4	8.0	clay	0.746
Lock 1989	3.137	281.6	6.5	clay	0.761
Mintaro 1989	3.662	394.4	7.0	heavy clay	0.762
Ungarra 1989	2.600	414.0	5.1	clay	0.728
Spalding(D)* 1989	4.120	305.6	6.5	clay loam	0.731
Wokurna 1989	3.167	295.0	8.3	sand loam	0.735

Sites A, B, C and D are the outrider sites described in Table 3.4

D_{rf}, D_t, D_l = graded membership for growing season rainfall, growing season temperature and length of growing season.

W_{rf}, W_t,W_l = weightings given to growing season rainfall, growing season temperature and length of growing season with respect to the importance of each compared to the others,and $W_{rf} + W_t + W_l = 1.0$.

D_{st}, D_{sd}, D_{pH}, D_{sl}, D_{ss} = graded membership for soil texture, soil depth, soil pH, slope and soil salinity.

W_{st}, W_{sd}, W_{pH}, W_{sl}, W_{ss} = weightings given to each soil variable w.r.t. each other, and $W_{st} + W_{sd} + W_{pH} + W_{sl} + W_{ss} = 1.0$.

Wc = comprehensive climate weighting.
Ws = comprehensive soil weighting.
A* = aggregate weighted index.

•Graded Membership

The Graded Membership Function expresses inexactness and allows it to be incorporated into a formal optimising procedure. It represents knowledge of how a variable affects a process. Coefficients are represented by intervals rather than exact values. This gives an estimate of the degree of membership to a particular characteristic that a varable has.

The degree of graded membership has been defined by Zadeh (1983). Let $\underline{c}$ be a set and $\underline{c}$ a member of that set. A fuzzy subset F of $\underline{c}$ is defined by a membership function mc that measures the degree to which $\underline{c}$ belongs to F.

An example of a graded membership u(x) of a considered variable (x) is;

$$u(x) = \begin{cases} 0 & x \leq v_1 \\ 1 - \dfrac{v_2 - x}{v_2 - v_1} & v_1 < x \leq v_2 \\ \dfrac{v_3 - x}{v_3 - v_2} & v_2 < x \leq v_3 \\ 0 & x > v_3 \end{cases} \qquad (3.2)$$

Where u(x) = degree of graded membership of x

v_1 = minimum value for which membership is valid.

v_2 = the optimal value for membership.

v_3 = the upper limit for membership.

x = measured value.

The Graded Membership Function can be represented in different forms according to the type of function represented. This depends on the concept of how one variable belongs to another. In constructing the following Graded Membership Functions, universal rules known to govern yields in wheat were used.

3.2.2 Degree of Graded Membership

Values used, the rules used and reasons for their choice are described in Table 3.2:

Table 3.2 The graded membership functions: values and rules used together with the reasons for their choice.

Variables	Membership Function	Rules	Reasons for Choice
A. Climate Growing Season Rainfall x_1 (mm)	$\mu_1(x_1)=\begin{cases}0\\ \frac{x_1-120}{480}\\ 1\\ 0.5\end{cases}$	if $x_1 < 120$ if $120 \le x_1 <$ 600 if $600 \le x_1 < 700$ if $x_1 \ge 700$	120mm considered minimum rainfall required to support yield, Figures 3.1 and 3.2. 600mm to 700mm is considered the optimum for wheat growth. > 700mm possible water logging& anoxic soil conditions. Wet conditions at harvest. Increased disease
Growing Season Temperature x_2 (°C)	$\mu_2(x_2)=\begin{cases}0\\ \sqrt{1-\frac{(15-x_2)^2}{100}}\\ 1\\ \sqrt{1-\frac{(23-x_2)^2}{100}}\\ 0\end{cases}$	if $x_2 < 5^{0}$ if $5^{0} \le x_2 < 15^{0}$ if 15^{0} $x_2 < 23^{0}$ if $23^{0} \le x_2 < 33^{0}$ if $x_2 \ge 33^{0}$	5°C No growth supported. Growth restrictions due to lower temperatures. 15 to 23° optimum temperature range to support growth. Growth restrictions due to higher temperatures. > 33°C growth stops. Sources: FAO 1978

Length of Growing Season x_3 (Days)	$\mu_3(x_3)=\begin{cases}0\\1-\frac{(120-x_3)}{45}\\1\\1-\frac{(x_3-150)}{200}\\0.5\end{cases}$	if $x_3 \le 75$ if $75 < x_3 \le 120$ if $120 < x_3 \le 150$ if $150 < x_3 \le 250$ if $x_3 > 250$	< 75 days, too short to provide yield Constraints due to short growing season. Optimum growing season for grain production.120 to150 days Constraints due to extended growing season. Excessive yield losses can occur. Source: FAO 1978
B. Soil Soil Texture x_4	$u_4(x_4)=\begin{cases}0.3\\0.6\\0.8\\0.9\\1.0\\0.6\\0.4\end{cases}$	if heavy clay if clay if sandy clay if sandy clay loam if sandy loam if clay loam if sand	Relative values from experimental results of the effect of soil texture and water holding capacity on wheat yield. Source W.A. Wheat Bulletin No. 4193 (1992).
Soil Depth x_5 (cm)	$\mu_5(x_5)=\begin{cases}0\\\frac{x_5-10}{30}\\1\end{cases}$	if $x_5 < 10$ if $10 \le x_5 < 40$ if $x_5 \ge 40$	Absolute restriction to production. Restrictions to full growth potential. Optimum soil depth for wheat growth.

Soil pH x_6	$\mu_6(x_6)=\begin{cases}0\\ 1-\frac{(6.5-x_6)}{2}\\ 1\\ \frac{9.5-x_6}{1.5}\\ 0.33\end{cases}$	if $x_6 < 4.5$ if $4.5 \leq x_6 < 6.5$ if $6.5 \leq x_6 < 8.0$ if $8.0 \leq x_6 < 9$ if $x_6 \geq 9$	Effect of soil pH on wheat growth. W.A. Dept of Agriculture Bulletin 4193.
Slope x_7 (%)	$\mu_7(x_7)=\begin{cases}1\\ \frac{(19-x_7)}{17}\\ 0.24\end{cases}$	if $0 \leq x_7 < 2$ if $2 \leq x_7 < 15$ if $x_7 \geq 15$	No effect on yield decreasing effect on yield. Major effects on yield.
Soil Salinity(EC_e) x_8 (ms)	$M_8(x_8)=\begin{cases}1.0\\ 0.8\\ 0.7\\ 0.6\\ 0.5\\ 0.3\\ 0.0\end{cases}$	If EC_e $0 \leq x_8 \leq 6$ " $6 < x_8 \leq 8$ " $8 < x_8 \leq 10$ " $10 < x_8 \leq 12$ " $12 < x_8 \leq 14$ " $14 < x_8 \leq 16$ " $x_8 > 16$	Effect of salinity on wheat yields (Relative Productivity). Source: Bevnstein 1964.

3.2.3 Expert Weight Determinations

Weightings (w) were assigned in the range 0.0 to 1.0 according to assessment of the importance of the variables with respect to each other in determining an outcome (Zadeh, 1983), such as wheat grain yield in this case. To help in decision making, weights were assigned to the variables expressing their relative interactive importance to each other in the way described earlier (section IV.III).

The weightings obtained were normalised to give a rating between 0.0 to 1.0. The weightings assigned and the reasons for their choice are as follows:

Climate Weightings

1. Growing Season Rainfall, W_{rf}

It has been shown under South Australian conditions that 60% - 70% of the variation in grain yield can be explained by differences in the growing season rainfall (French and Schultz, 1984; Greacen and Hignett, 1976). Therefore, this variable was considered in the most important category and weighted at 0.6.

2. Mean Growing Season Temperature, W_t

Three degrees centigrade above or below the optimum seasonal growing temperatures causes 2 - 4% loss in wheat yields (Arnon, 1972; Asana and Williams, 1965). Ranges of W_t within these limits are usual in the South Australian wheat lands except for occasional frosts and hot winds during flowering and grain setting. Hence, in comparison to W_{rf}, W_t was rated marginally important and given a weighting of 0.2.

3. Length of Growing Season, W_l

In South Australia the optimum W_l for the varieties of wheat grown is in the range 150 - 200 days (Hollamby pers. comm.). The W_l is generally available. Therefore in comparison to W_{rf}, W_l was considered marginally important and was weighted at 0.2.

Soil Weightings

1.Soil Texture, W_{st}

Soil texture determines the rate of water infiltration and the water holding capacity of soils. For semi-arid regions, this was considered important and hence a weighting of 0.3 was assigned to W_{st}.

2. Soil pH, W_{pH}

Soil pH's < 5.5 and > 8.5 influence the availability, uptake and translocation of both macro and micro-nutrients. Outside this range, elements can be taken up at toxic levels. Hence, pH values outside this range can limit growth and yield. Only two soils from the test sites (Table 3.1) fell outside this range. However, 14 out of the 30 soils had a pH of 8.5. Therefore, the influence of pH was considered important and given a weighting of 0.3.

3.Soil Depth, W_{sd}

Together with texture, soil depth determines the amount of water that can be held in a soil for potential plant use. Wheat is a relatively shallow rooted plant, so most of the root length is found in the top 50 cm (Forrest et al, 1984), even though a small proportion of roots can penetrate to depths of 90 cm and lower. This suggests that in the wheat growing soils of South Australia the rooting depths are adequate. Taking the above considerations into account, soil depth was considered marginally important and given a weighting of 0.2.

4. Soil Salinity W_{ss} and Soil Slope W_{sl}

Local wheat is grown on soils with electrical conductivities (Ec) less than 2 (Forrest et al 1984) and is not grown on slopes greater than 7%. Therefore, these variables are considered least important of the soil variables in determining yield and were both given a weighting of 0.1.

Overall Comprehensive Climate (Wc) and Soil (Ws) Weightings

As growing season rainfall can explain 50 - 70% of the variation found in wheat yield (Greacen and Hignett 1976), Wc was assigned a weighting of 0.6, and hence Ws was assigned a weighting of 0.4.

3.2.4 Solving for Weightings by Least Square analysis

To check the expert weightings a least squares analysis was performed. The data given in Table 3.1 does not include information for non-optimal growing conditions for length of growing season, mean growing season temperature, soil depth, soil salinity and slope. To obtain weightings for these variables, additional relations covering yield and the governing degrees of membership were generated using the following empirical rules. The yields given in Table 3.1 were adjusted using these rules. The degrees of memberships were adjusted to the same extent as the yields using the membership functions given in Table 3.2 .

The rules used were:

a) Length of growing season: The yields were decreased by 7% for each week delay from optimum sowing time (French and Schultz, 1984). One week delay was considered, giving a 113 days growing season. This produced a graded membership of 0.8 (Table3.2);

b) Mean growing season temperature: Three degrees above or below the optimum temperature range yields are decreased by 3% (Arnon, 1972). Yields are decreased by 3% to simulate a three degree (°C) increase above the optimum temperature range. For a three degree above-optimum mean temperature, the graded membership is 0.95 (Table3.2);

c) Soil Depth: Above 40cm, each cm reduction in soil depth results in 1.7% reduction in yield. The soil depth was taken as 38cm, and the yield reduced by 3.4% (Carter, 1984). The degree of membership for this depth is 0.93 (Table 3.2);

d) Soil Salinity: The soil salinity was taken as 7mS, and thus the yield was reduced by 10% (Table 3.3). The graded membership for a salinity of 7mS is 0.8 (Table3.2);

e) Slope; the rules for reduction in yield are given in Table (3.4). For a slope of 9% the yield was reduced by 10%. The graded membership for this slope is 0.6 (Table3.2).

These five rules were applied one at a time to the data sets in Table 3.1 to give 150 extra data sets; 180 including those in Table 3.1.

The equation governing yield and the aggregated weighted index (Fig.4) is,

$$Y' = a10^{bA^*} \qquad (3.3)$$

Where: a and b are constants for a given region

Y' = yield

A^* = the aggregated weighted index .

$$A^* = Wc\ (W_{rf}\ D_{rf} + W_t D_t + W_l\ D_l) + Ws\ (W_{st}\ D_{st} + W_{sd}\ D_{sd} + W_{pH}\ D_{pH} + W_{sl}\ D_{sl} + W_{ss} D_{ss})$$

This is the linear form of the interaction matrix (equation 3.1).

The linear form of equation (3.3) is:

$$\lg Y' = \lg a + bA^*$$

From the actual yield given in Table 3.1, plus those obtained using the rules, a minimizing least squares analysis was carried out:

$$\text{Min. } Q = \sum_{i=1}^{n} (\lg Y_i - \lg Y_i')^2$$

where Q = sum of the obtained yield minus the predicted yield squared.

Y_i = the yields given in Table 1 and those generated using the given rules.

Y_i' = calculated yield from equation (3.3).

From the equation, values for the weightings, W_{rf}, W_t, W_l, W_{st}, W_{sd}, W_{pH}, W_{sl}, and W_{ss} were obtained.

Table 3.3 The effect of salinity on reducting wheat yield.

Soil Salinity (Ec at 25oC)(ms)	Yield Reduction (%)
<6	0
6 to 9	10
9 to 14	25
> 14	50

Source: Bernstein (1964)

Table 3.4 Effect of Slope on Relative Productivity

Topographic Rating	Slope (%)	Relative Production Rating
Level to slightly undulating	0 to 3	1.00
Very gently undulating	3 to 5	0.95
Gently undulating	5 to 10	0.90
Undulating	10 to 20	0.85

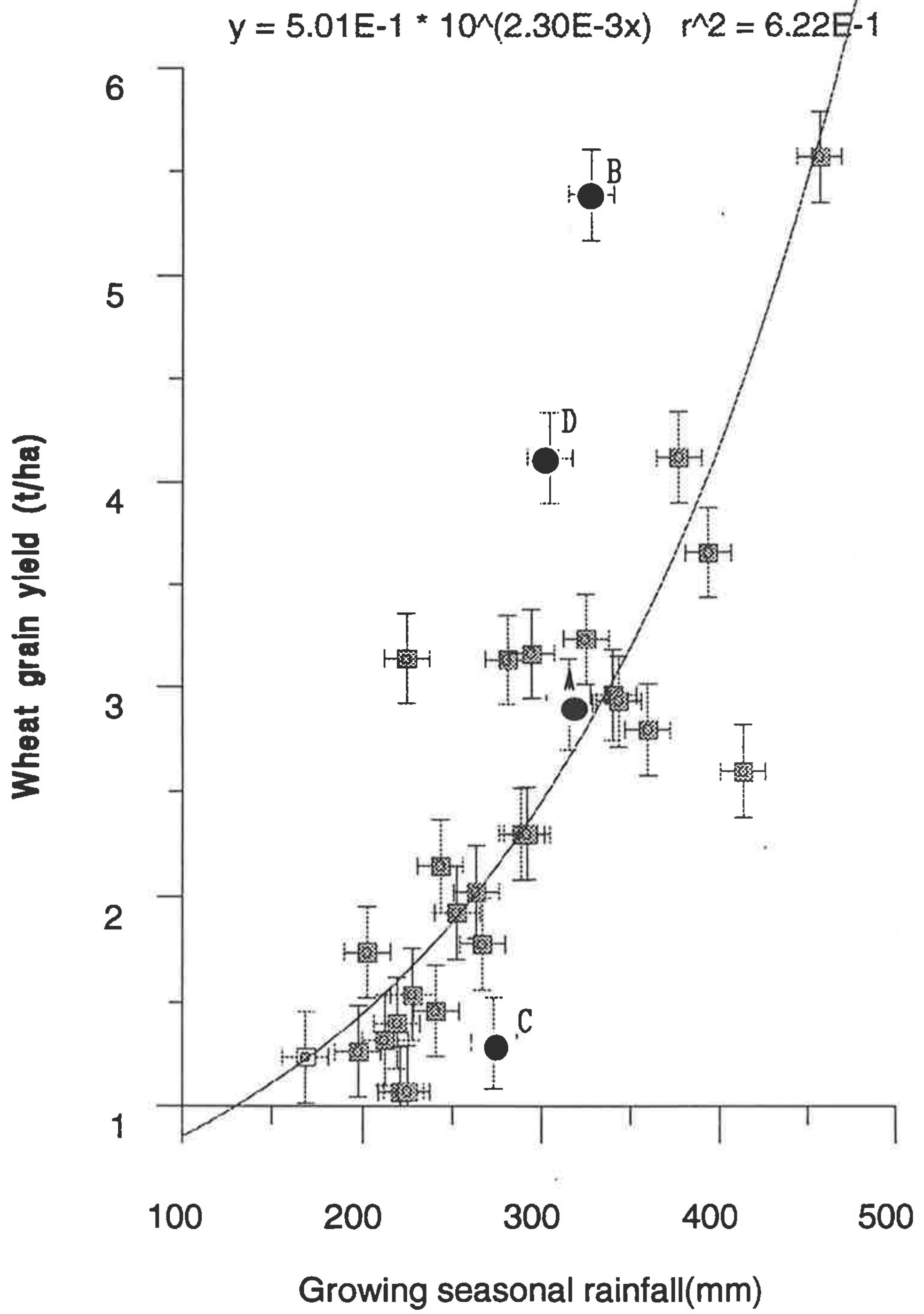
Source: Walker, P.J.; NSW Conservation Service

3.3 RESULTS AND DISCUSSIONS

3.3.1 Growing Season Rainfall - Yield Relationships

Figure 3.1 gives the grain-yield versus growing season rainfall relationship which includes all site values. This exponential regression explains 62% of the variance. A linear regression explained 60%. These levels of explanation are

Fig 3.1 Wheat grain yield plotted against growing seasonal rainfall. All data points included



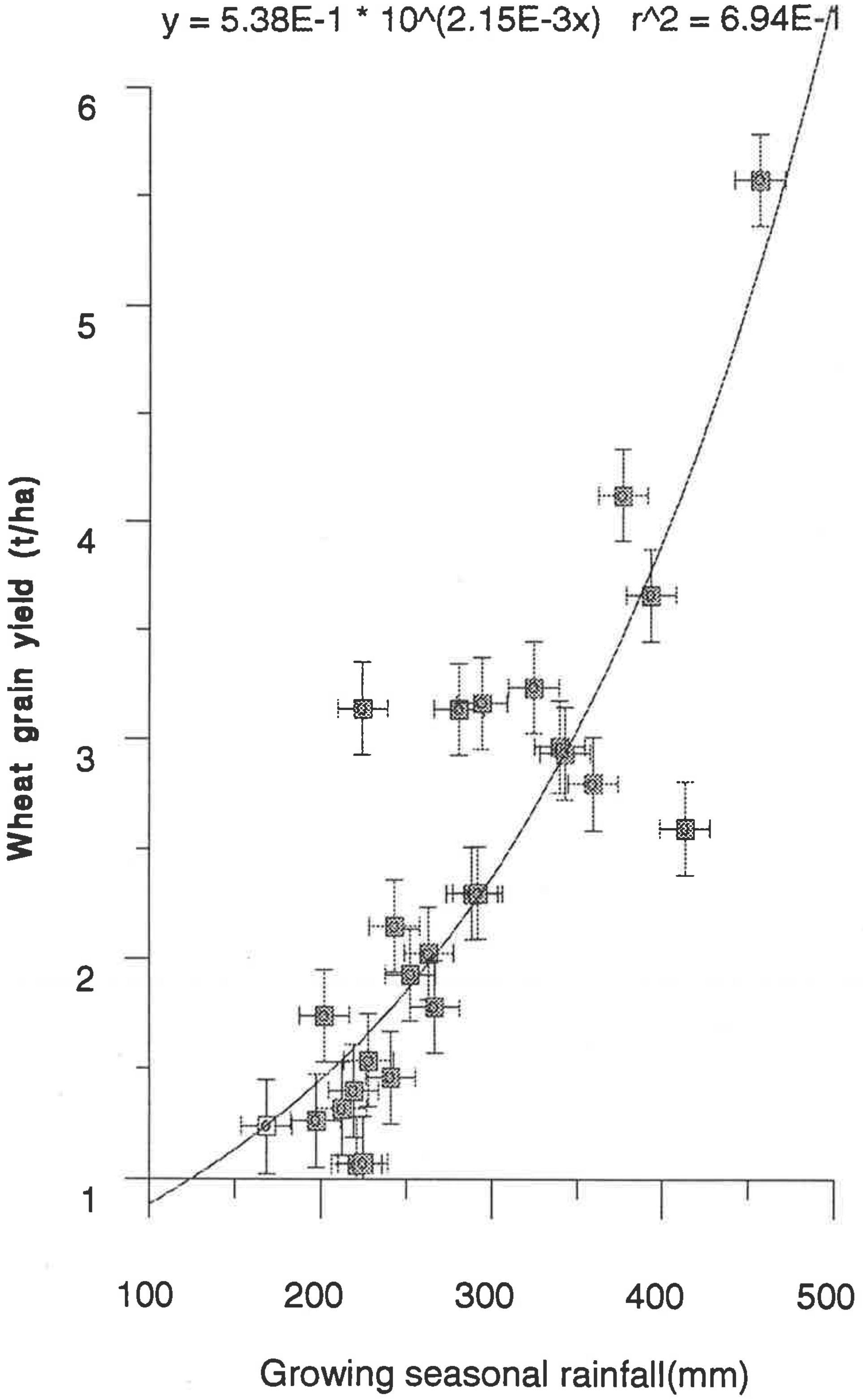
very similar to those given for wheat yield response to growing season rainfall in several regions of Australia (Cornish 1950; French and Schultz 1984, Perry 1987). Figure 3.2 gives the analysis with site values A, B, C and D removed from the analysis for the reasons given in Table 3.5.

Table 3.5 History and Reasons for Omission and Increase/Decrease in Yield for Sites, A, B, C and D (taken from Figure 4.4)

Site Identification	History	Reason for Omission	Increase/Decrease in yield (%)
A	Nitrogen deficiency	Lowered soil fertility	- 22
B	Long period of pasture rotations	Increased soil fertility	+20
C	Heavy rain 10 days before harvest	Resulting decrease in yield (grain lost by head shattering)	- 32
D	High pre-sowing rainfall (100mm in March)	Potential to increase yield	+ 46

The omission of these sites increases the yield/growing-season-rainfall models explanatory value to 69% of the variance (Figure 3.2). A linear regression analysis explains 71% of the variance. At this level of analysis it seems that a linear (French and Schultz 1984) and an exponential model have equal explanatory power.

Fig 3.2 Wheat grain yield plotted against growing seasonal rainfall with outriders omitted



3.3.2 Aggregated Knowledge Weighted Index - Yield Relationships

Figure 3.3 gives the plot of yield against the aggregated knowledge weighted index, A*, Relation 3.1. The values are presented in Table 3.1. This explains 87% of the variance (Fig. 3.3). Figure 3.4 shows the same plot with the 'outrider' sites A, B, C and D omitted for the reasons given in Table 3.5. This increased the explanatory power to 95%. This is of high predictive value and is an improvement on previous models where only the growing season rainfall was considered (French and Schultz, 1984).

3.3.3 Analysis of Weightings

Section 3.2.3 gave the decision maker, (expert) an estimate of the weightings and reasons used to give assessment of the importance of the variables considered with respect to each other. These are to be compared with the least square assessed weightings, the derivation of which is described in Section 3.2.4. The explanation of the variance (R^2) given by the expert weightings is 0.95 (Figure 3.4), compared to 0.96 for the least squared weightings. Table 3.6 gives the comparison of the individual expert and least square weightings. The agreement between the two methods of weighting shows the expert weighting described in this work can be used to estimate yields. This could be useful where there is insufficient empirical data.

Table 3.6 Comparison between expert and least square adjusted weightings

Variables	Expert Weightings	Least Square adjusted weightings	Differences (%)
1. Climate			
Overall weightings (W_C)	0.6	0.59	+1.6
Growing season rainfall (W_{rf})	0.6	0.68	-13.3
Length of growing season (W_l)	0.2	0.13	+35
Mean growing season temperature (W_t)	0.2	0.18	+10

Fig 3.3 Wheat grain yield plotted against the aggregated weighted index. All data points included

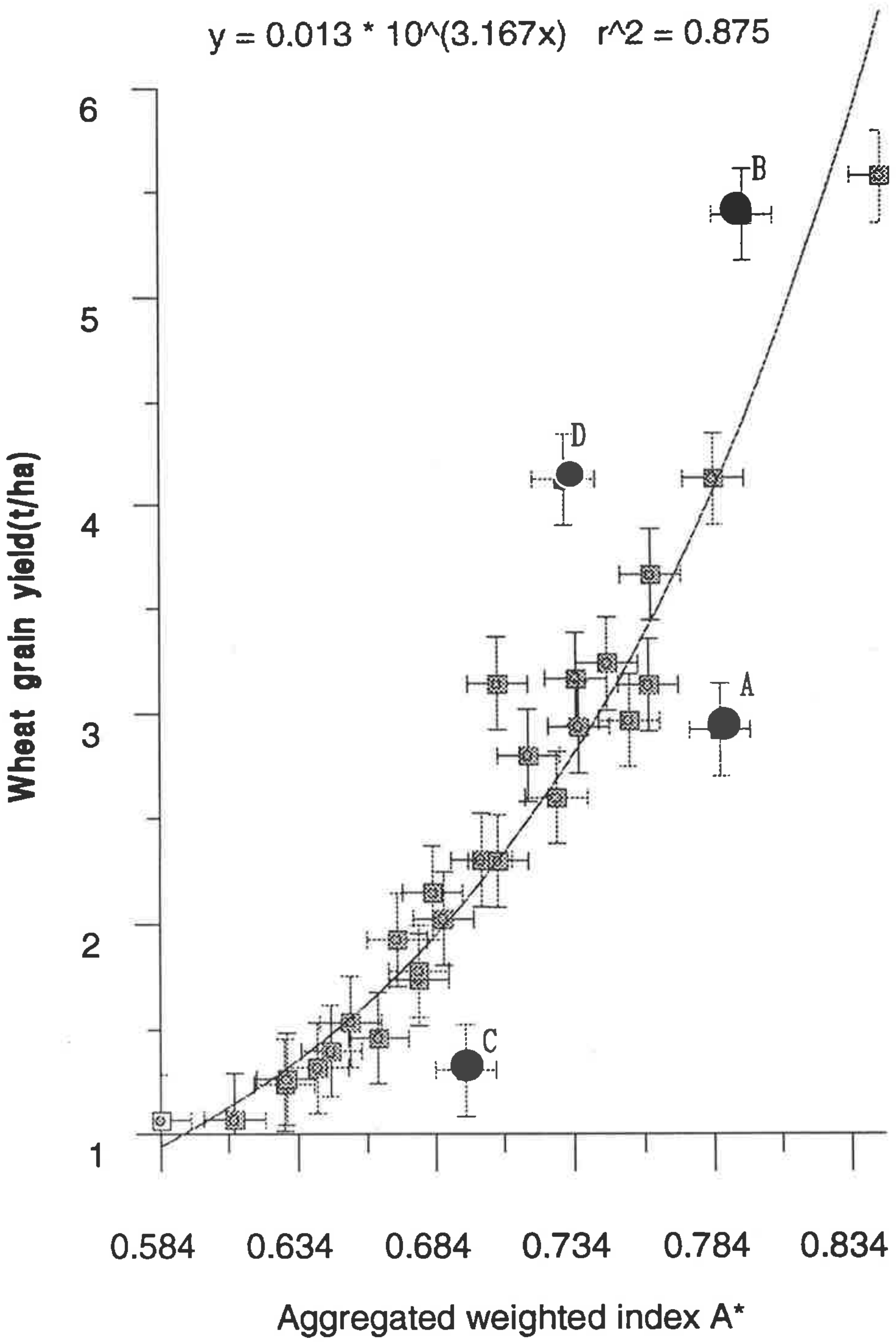
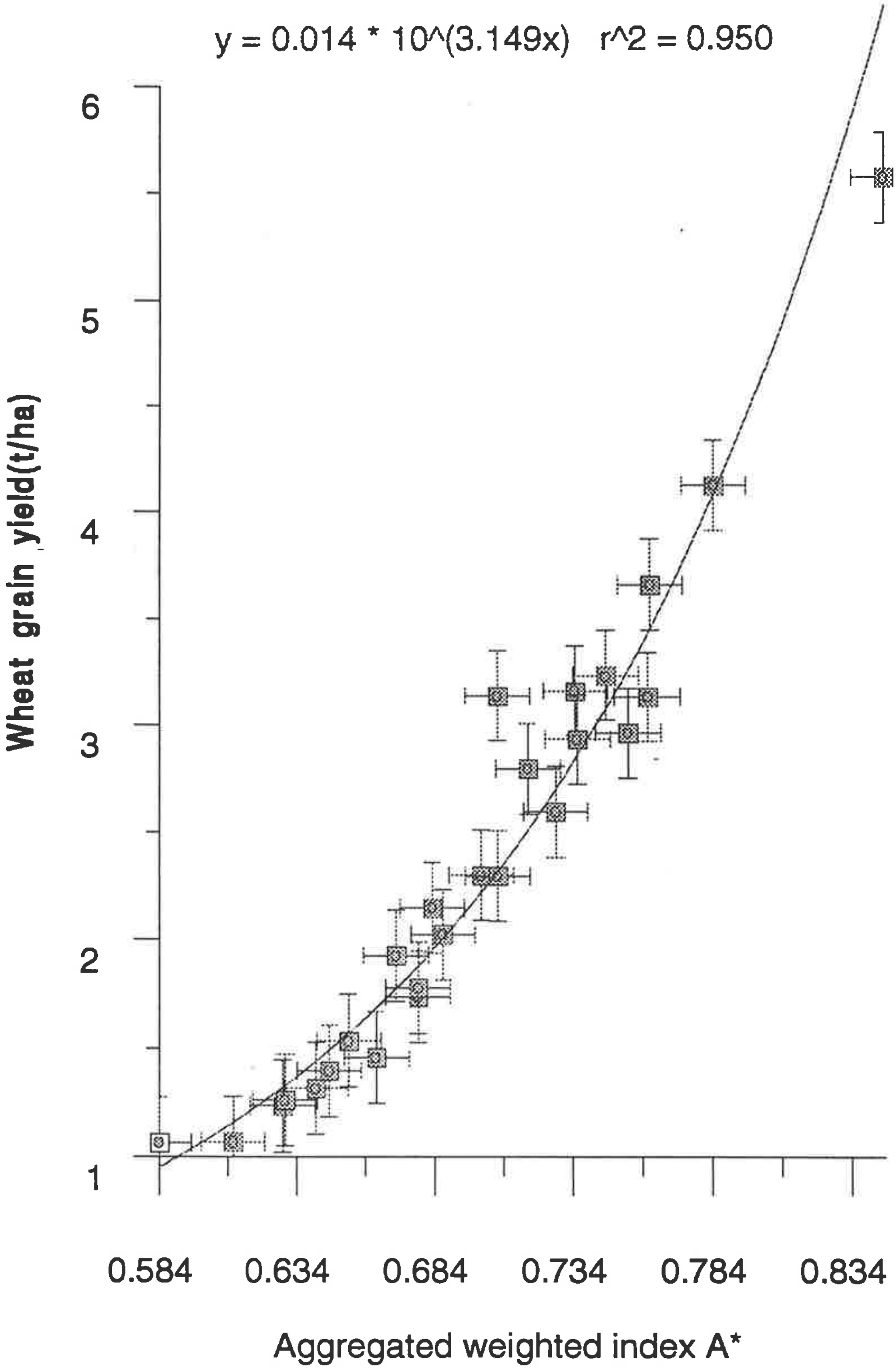


Fig 3.4 Wheat grain yield plotted against the aggregated weighted index with outriders omitted. Based on expert weightings.

y = 0.014 * 10^(3.149x)   r^2 = 0.950



2. Soil			
Overall weighting (W_S)	0.4	0.41	-2.5
Soil pH (W_{pH})	0.3	0.24	+20
Soil texture (W_{st})	0.3	0.20	+33
Soil depth (W_{sd})	0.2	0.24	-20
Slope (W_{sl})	0.1	0.21	-110
Soil salinity (W_{ss})	0.1	0.11	-10

The largest discrepancy between the two systems of weightings are those for slope. This suggests that the slope ratings used in the least square assessment (Table 3.4) have too high or low an effect on yield in comparison to the weightings of the other variables. This highlights that the effect of slope requires further investigation.

Overall Weightings

Effects of changes in the overall comprehensive climate (W_C) and soil (W_S) weightings on the explanatory value (R^2) of equation 3.1 (A*) are shown in Table 3.7.

Table 3.7 The effect of changes in the comprehensive Climate (Wc) and Soil (Ws) weightings on the predictive value of relation 3.1 (A*)

Comprehensive Climate Weighting (Wc)	Comprehensive Soil Weighting (Ws)	Explanatory Value (R^2)
0.7	0.3	0.92
0.6	0.4	0.95
0.5	0.5	0.90

Taking these results together with the overall weightings obtained from the least squares analysis (Table 3.6) suggested that under the conditions studied about 60% of the yield is determined by climate and 40% by soil variables. The importance of rainfall is likely to increase and soil factors decrease in importance as the rainfall decreases and becomes the limiting factor. The reverse could occur at high rainfalls, such as > 700mm, when soil factors could become more limiting.

The integrated approach taken here gives a methodology for determining the relative importance of the soil and climate variables in determining yield. This knowledge can be used to assess the capability of given parcel of land for wheat production.

The aggregated knowledge model gives a computational framework for dealing with complex interactions which have not (or cannot) be related experimentally. Additionally, it provides a mechanism for reasoning about datasets that always remain incomplete, as is often the case when. the dataset is not large enough to use regression analysis. In addition, when empirical data do not fit the membership function, the explanations offered for outriders provide a sound knowledge acquisition strategy. For example, Figure 3.3 values from trial sites A, B, C and D indicate variance with the expected yield membership function constructed from climatic and soil variables. The reasons given for these outriders are presented in Table 3.5. From a knowledge acquisition perspective, outriders such as in A, B, C and D provide an interesting basis on which to focus discussion on exceptional or unusual cases. The explanations for the outriders define the boundaries of domain knowledge. Their explanation requires expert intervention and can be used to elicit knowledge-base rules.

The type of knowledge incorporated analysis described here could be used to consider the combined effect of variables which cannot be related in quantitative terms, eg the effect of type and level of management and the environmental effects of different land management practices.

Chapter 4. Yield in Field Peas
Fuzzy Sets in Aggregated Knowledge Construction

Chapter 3 demonstrated that local user knowledge could be used to obtain weighting sets that correspond with weightings derived from a least square analysis. To further test the effectiveness of expert/user information in obtaining weightings, this information was used to predict yield in field peas. This was done because the data set available was not large enough to obtain weightings by a least square analysis.

4.1 Introduction

This model aggregates available user/expert knowledge in a way that combines different measures known to influence crop yield. This is done in an interaction matrix of climate and soil variables. The matrix is a weighted summation of graded memberships of variables scaled for their importance in determining crop yield and aggregated into an integrated value. The development of methods such as this is important as they give us a computational framework for dealing with: (i) complex interactions which have not or cannot be related experimentally; (ii) datasets that always remain incomplete and (iii) incorporate expert knowledge.

4.2 Method

Data concerning crop yield, rainfall, soil texture, soil pH, etc at various test sites was obtained from The South Australian Department of Agriculture. The knowledge based model was constructed using the interaction matrix which took into account the climatic and soil variables. The general relationships and membership function for the interaction matrix has been described in chapter 3, relation 3.1 and 3.2.

Table 4.1 Site and year of trial, yield, annual rainfall, growing seansonal rainfall, soil PH, soil texture and the comprehensive knowledge weighted index (A*) obtained from relation(1)

	Site and year	pea yield(t/ha)	annual rainfall(mm)	seasonal rainfall(mm)	soil PH	soil texture	A*
1	Mintaro1990(A)	1.42	401	326	6.8	Blockselfmulch	0.904
2	Laura1990(B)	1.75	411	317	8.2	clay loam	0.796
3	Balaklava1990	0.68	281	233.6	8.5	Loam	0.58
4	Curramulka1990	1.12	325	311	8.2	loam sandy	0.767
5	Riverton1990	1.29	516.5	346.2	7.5	clay	0.82
6	Kinsford1990	1.04	516.5	346.2	8.4	clay	0.73
7	Lock 1990	1.21	365	264	7.3	sandy clay loam	0.776
8	Tumby bay1990	1.49	442.6	336	8.23	sandy clay loam	0.811
9	Balaklava1989	0.73	277	200	7.2	clay	0.63
10	Tumby bay1989	2.06	403.3	357	7.7	sandy clay loam	0.916
11	Yeelan1989	2.28	477	418.2	7.5	clay loam	0.958
12	Mintaro1989	1.97	525	384	5.7	red brow earth	0.876
13	Clare1989(C)	1.42	538	384	5.4	red brow earth	0.846
14	Curramulka1989	1.82	404.5	351	8	red brow earth	0.907
15	Laura1989(D)	1.78	515	286	7.4	silty deposite	0.809
16	Lock 1989	2.22	432	415	7.2	loamy sand	0.962
17	Mundulla1989	2.64	475	311	7.5	red brown loam	0.96
18	Turretfield1989	1.85	523	442	6.1	sand clay loam	0.89

Site A, B, C and D are the outrider sites described in table4.4

4.3 Degree of Graded Membership and Weightings Used

Values used and reasons for their choice are described as follows:

Degree of Graded Membership

(a) Climate variables

(i) Growing seasonal rainfall.

The graded membership for growing seasonal rainfall was determined using equation 3.2. The values used and the reasons for their choice are given in table 4.2.

Table 4.2 Growing season rainfall values assigment and reasons

variable assigment	**reason**
v_1= 200mm	minimum seasonal rainfall to give a reasonable yield (see fig 4.4).
v_2 = 400mm	this value was chosen considering fig 4.4 and work quoted by Arnon (1972) which considers that a growing season rainfall of greater than 300mm is required to produce a satisfactory crop.
v_3 = 650mm	growing season rainfall in excess of the optimum leads to water logging, anaerobic soil conditions and loss of nutrients. Two to five days of waterlogging during the growing season can reduce yields by 30 to 60% (Summerfield,1985).

(ii) Temperature and Length of Growing Season.

Trial sites were chosen on the basis of optimum temperature and the growing season. Hence, the graded membership for temperature and growing season was taken as 1.

(b) Soil Variables

(i).Soil pH.

The graded membership for soil pH was determined using the following equation

$$u(x_{pH}) = \begin{cases} 0 & x_{pH} < 5.0 \\ \dfrac{x_{pH} - 5.0}{1.5} & 5.0 \leq x_{pH} < 6.5 \\ 1 & 6.5 \leq x_{pH} < 8.0 \\ \dfrac{8.5 - x_{pH}}{0.5} & 8.0 \leq x_{pH} < 8.5 \\ 0 & x_{pH} \geq 8.5 \end{cases}$$

The reasons for selecting these values were:

Makashtzva (1984) gave the optimum pH range for the growth of peas as 6.8 to 7.4. Pea grow best in slightly acid soils at pH around 6.5 (Small, 1946). Most ryzobial strains fail to noduate in media as acidic as pH 5.0 and cause marked reductions in growth (Sutcliffe 1977). At soil pH>8.5 yields are reduced.

(ii) Soil Texture, $u(x_{st})$

The degree of graded membership for soil texture was allocated, with given reasons, as shown in table 4.3.

Table 4.3 Graded Membership for Soil texture classes.

	Graded Membership	Soil Texture Class
$u(x_{st})=$	0	Heavy clay - there have a high mechanical resistance and restrict pea tap root growth.The possibility of water logging poor aeration and nodulation are increased.
	0.3	Loamy clay, silty clay: compaction in soils of this texture can limit root growth.
	1.0	Self mulching clay.
	0.4	Medium to light clay.
	0.8	Clay loams, silty clay loam, fine sandy clay loam. The clay content considered to give some slight restriction to growth.
	0.8	Sandy loam.
	0.6	Loamy sand, sands: Water restrictions and stress during growth

Weightings

Weightings (w_i) were assigned in the range of 0.0 to 1.0 according to assessment of the importance of the variables with respect to each other in determining an outcome (Zadeh, 1983). The weightings assigned and reasons for their choice are as follows:

(a) Climatic Weightings

(i) Growing season rainfall (W_{rf})=0.6: This value was chosen as about 60% of the variance in yield can be explained by this rainfall. (Fig 4.5.)

(ii) Growing season temperature (W_t) = 0.2: The growing season temperature at the trial site was in the range considered optimum for pea plant growth and pod development which was 12 to 16°C and 16 to 20°C, respectively. Hence W_t was considered to have only a small effect on yield.

(iii) Length of Growing Season (W_l) = 0.2: The optimum growing season for peas is relatively short, 90 to 150 days. This is generally provided at the trial sites. Hence it is given a low explanatory weighting.

(b) Soil Weightings

(i) Soil depths (W_{sd}) = 0.3: For unrestricted growth, peas require soil depths of > 100cm. Hence a comparative weighting of 0.3 was given to allow for this requirement.

However some had pHs> 8.0 and < 6.5, so a weight of 0.3 was allotted to account for a slight influence of pH.

(iii) Soil Texture (W_{st}) = 0.2: Peas are relatively insensitive to soil texture, relative to soil depth and pH. Hence, W_{st} was given a low weighting.

(iv) Slope (W_{sl}) = 0.2: Peas are not planted on steeper slopes. Hence slope was given a relatively lower weighting.

4.4 Results and Discussion

The relationship between annual rainfall and yield is given in fig 4.1. This can only account for 26% of the variance (R^2) and has no predictive value.

In fig 4.2, yield values from trial sites marked A, B, C and D in fig 4.1 were removed from the analysis for the reasons given in table 4.4. The omission of the results obtained at these sites only increased the explained variance to 32%, which again was too low to be predictively useful.

Fig 4.1 Annual rainfall againt pea yield. All data point included

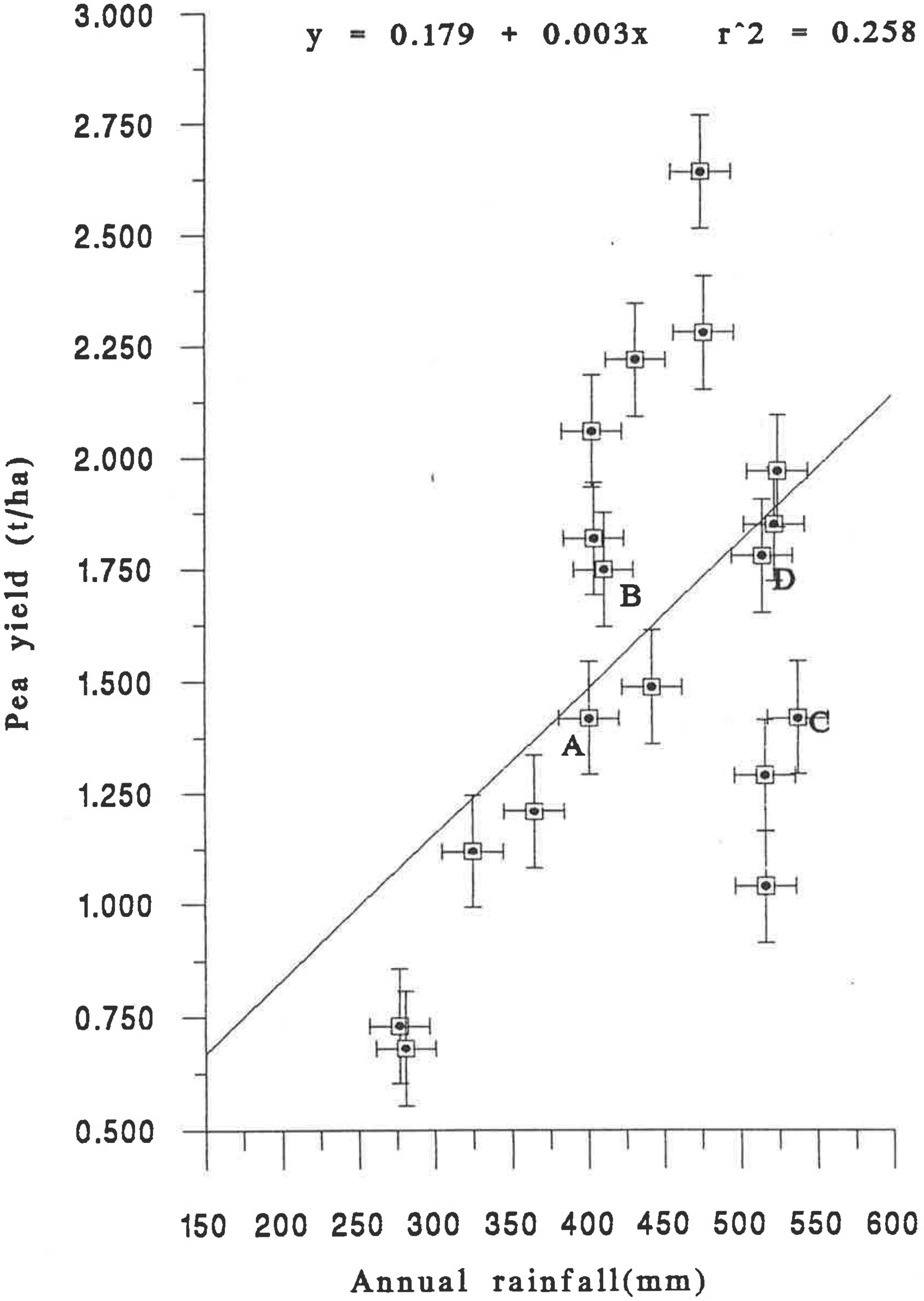


Fig 4.2 Pea yield plotted against annual rainfall with outriders omitted

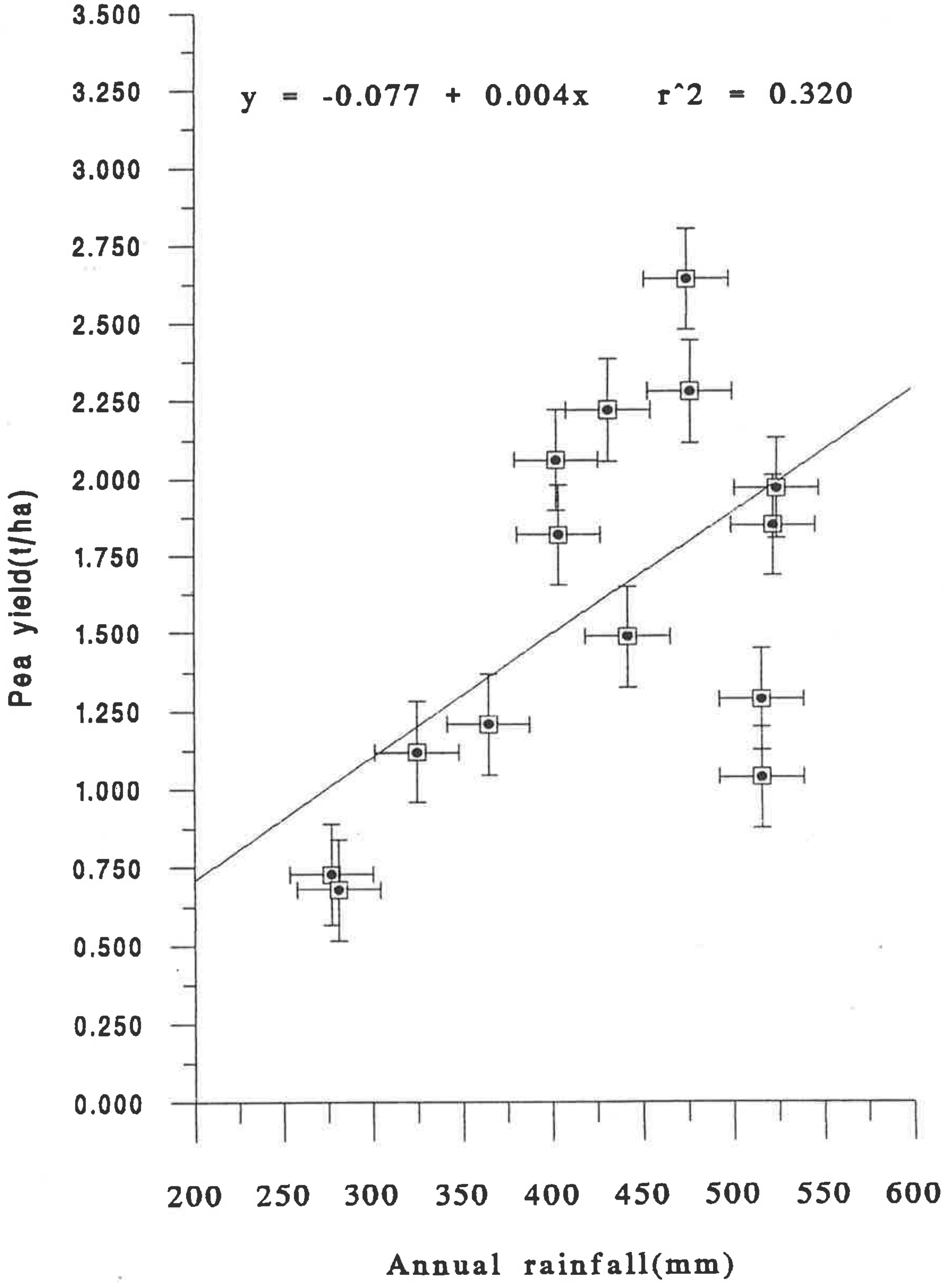


Table 4.4 History and reasons for omitting data from denoted trial sites.

Site Ident.	History	Reasons for omission
A	Site previously continually cropped with a wheat barley rotation.	Lowered soil fertility
B	Previous rotations contained a high component of medic pasture phases (pasture/oats/ pasture/wheat/pasture).	Increased soil fertility
C	Late sowing of pea crop and seed borne Ascochyts.	Shorter growing season.
D	Very high presowing rainfall (March, 130mm)	High soil moisture store at sowing giving the potential to increase yield.

Fig 4.3 gives the yield growing season rainfall relationship which includes all site values. In this analysis, 39% of the variance is explained. This higher explanatory value is to be expected as the growing season rainfall is more relevant to the yield than the annual rainfall. Fig 4.4 gives the analysis with site values A. B, C and D omitted for the reasons given in table 4.4. Without these sites the model explains 48% of the variance.

Fitting an exponential relation increases the explanatory value of the analysis to 58%, fig 4.5.

This is approaching the explanatory value (60%-70%) of growing season rainfall for wheat yields in South Australia (French, 1984). An exponential relationship would be expected to give a better explanation of the effect of growing season rainfall on yield. Initial rainfall increments over the minimum required to support production give a small rate of yield increase. Beyond this, additional rainfall gives a rapid increase in yield until a maximum plateau is reached. Further increases in rainfall can lead to yield reductions due to effects such as water logging, nutrient leaching, lodging, etc.

Fig 4.3 Pea yield plotted against growing seasonal rainfall. Alldata points included

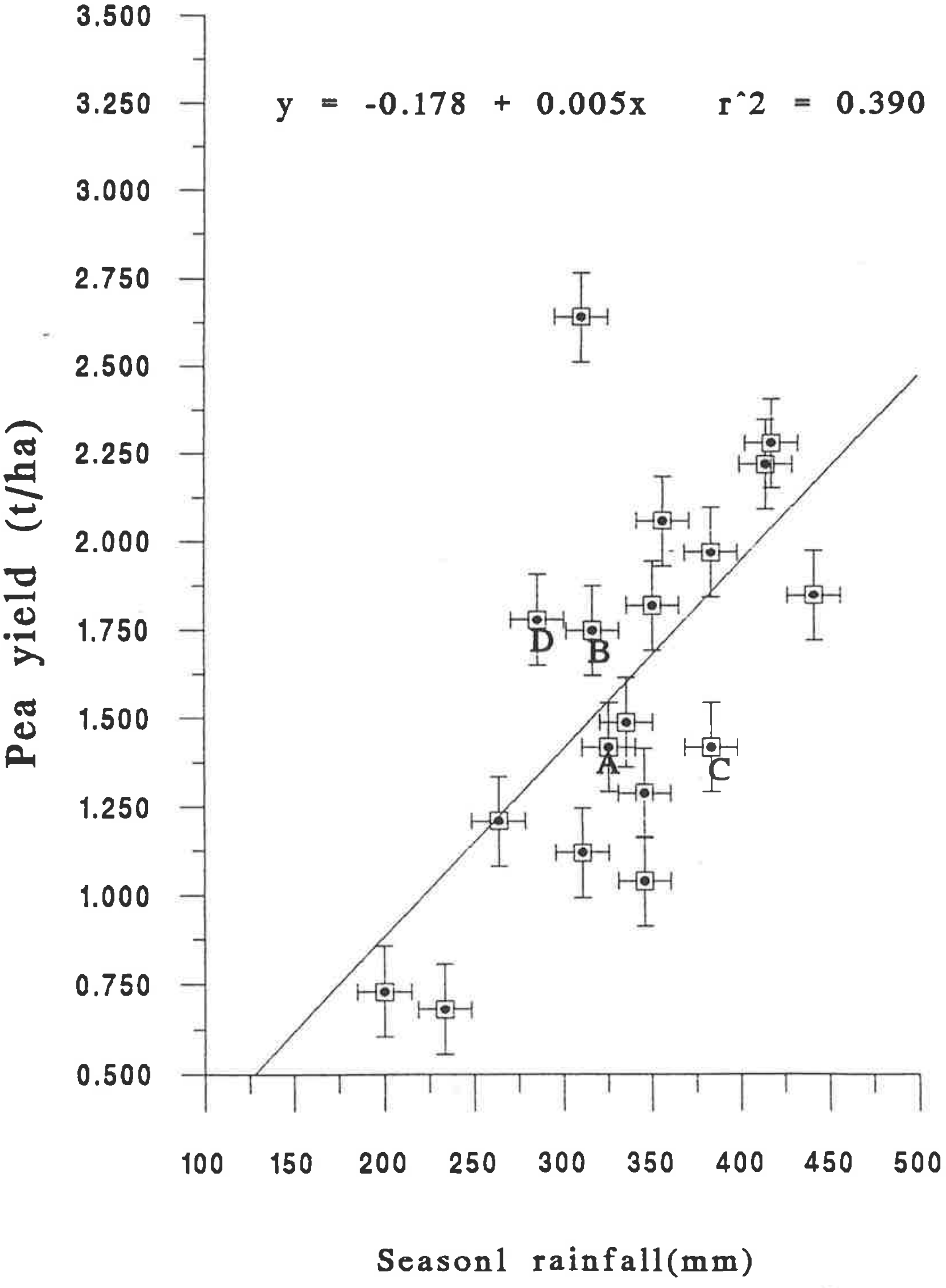


Fig 4.4 Pea yield plotted against seasonal rainfall with outriders omitted

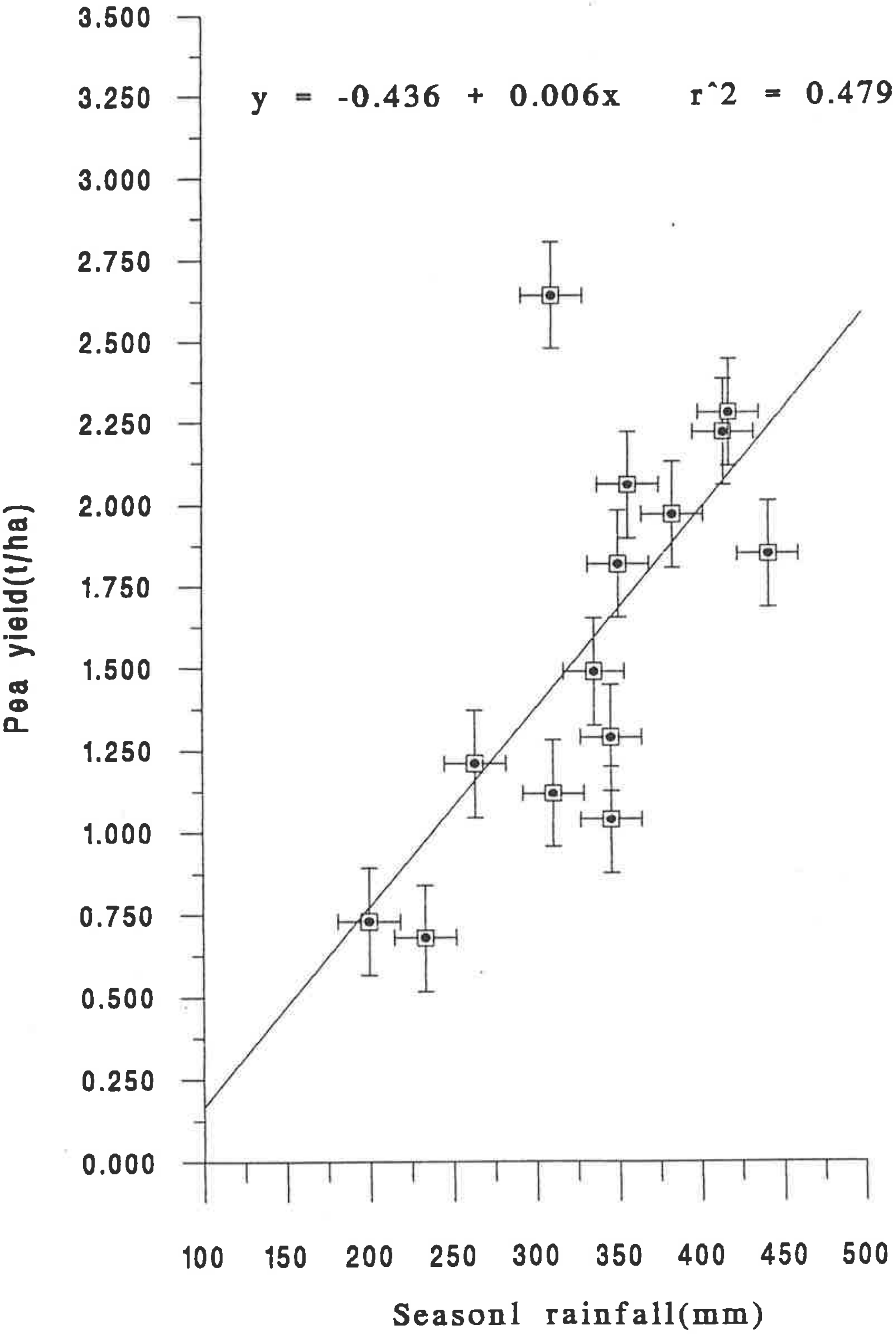


Fig 4.5 Pea yield plotted as an exponential against seasonal rainfall with outriders omitted

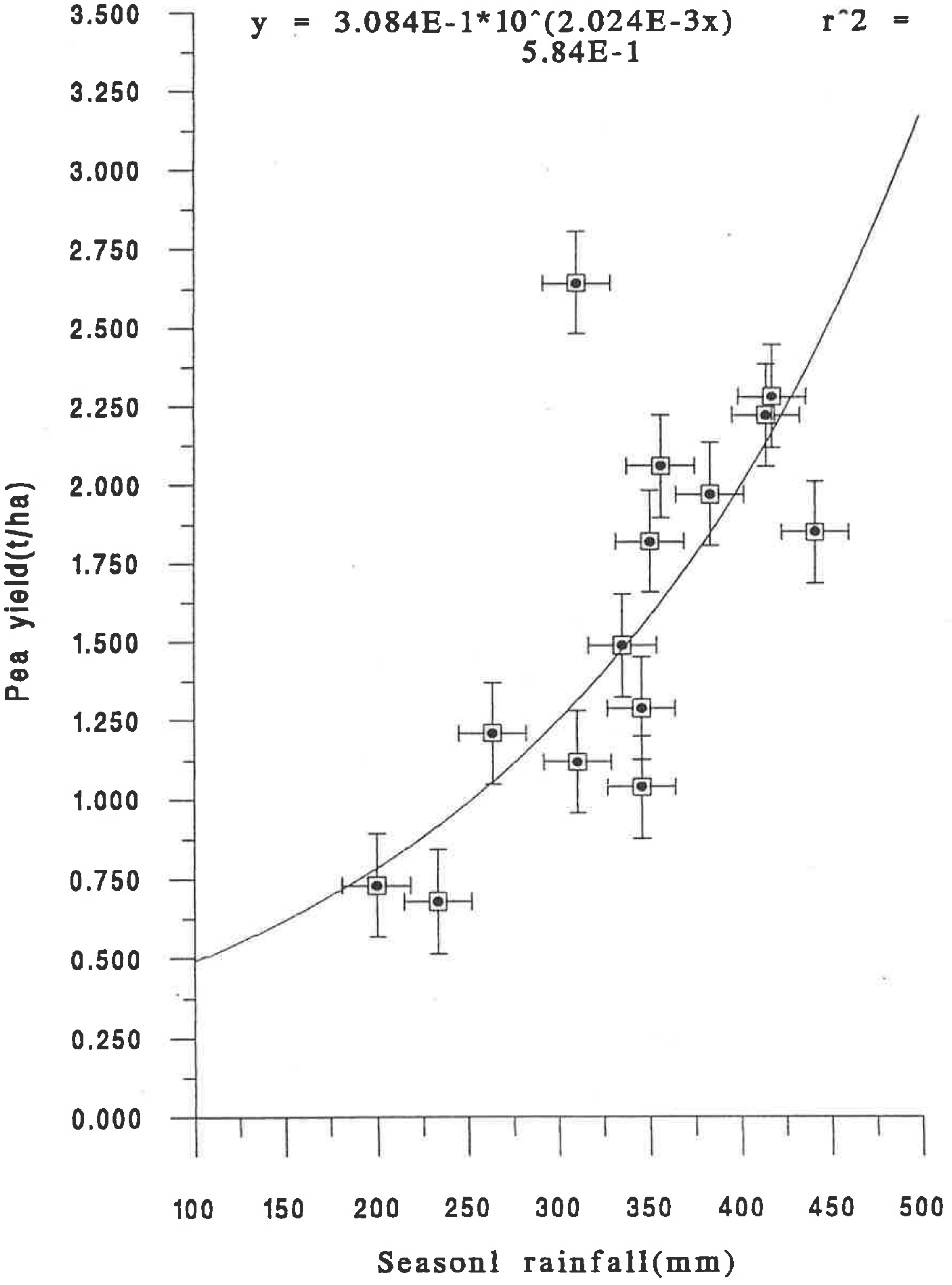


Fig 4.6 is the plot of yield against the knowledge weighted growing season climate versus soil factor index (aggregated weighted index - A*, relation 3.1). The values of the A* calculated for the various trial sites are given in table 4.1. With reference to the results in fig 4.5, an exponential analysis was used. In fig 4.6 all data was included. This relationship accounted for 87% of the variance.

In fig 4.7 the data points A, B, C and D were omitted for the reasons given in table 3.4. This increases the explanation of the variance to 97%.

This level of explanation gives a highly predictive model, proving that expert weighting can used in the model to predict productivity.

Effects of changes in the overall "comprehensive" climate (Wc) and soil (Ws) weighting indices on the explanatory value (R^2) of the model given in fig 4.7 are shown in table 4.5.

Table 4.5 The effect of changes in the comprehensive climate/soil indice weightings on the A*.

Comprehensive Climate Weighting	Comprehensive Soil Weighting	Explanatory Value (R^2)
0.7	0.3	0.935
0.6	0.4	0.964
0.5	0.5	0.972
0.4	0.6	0.945

Fig 4.6 Pea yield plotted against the aggregated weighted index. All data points included

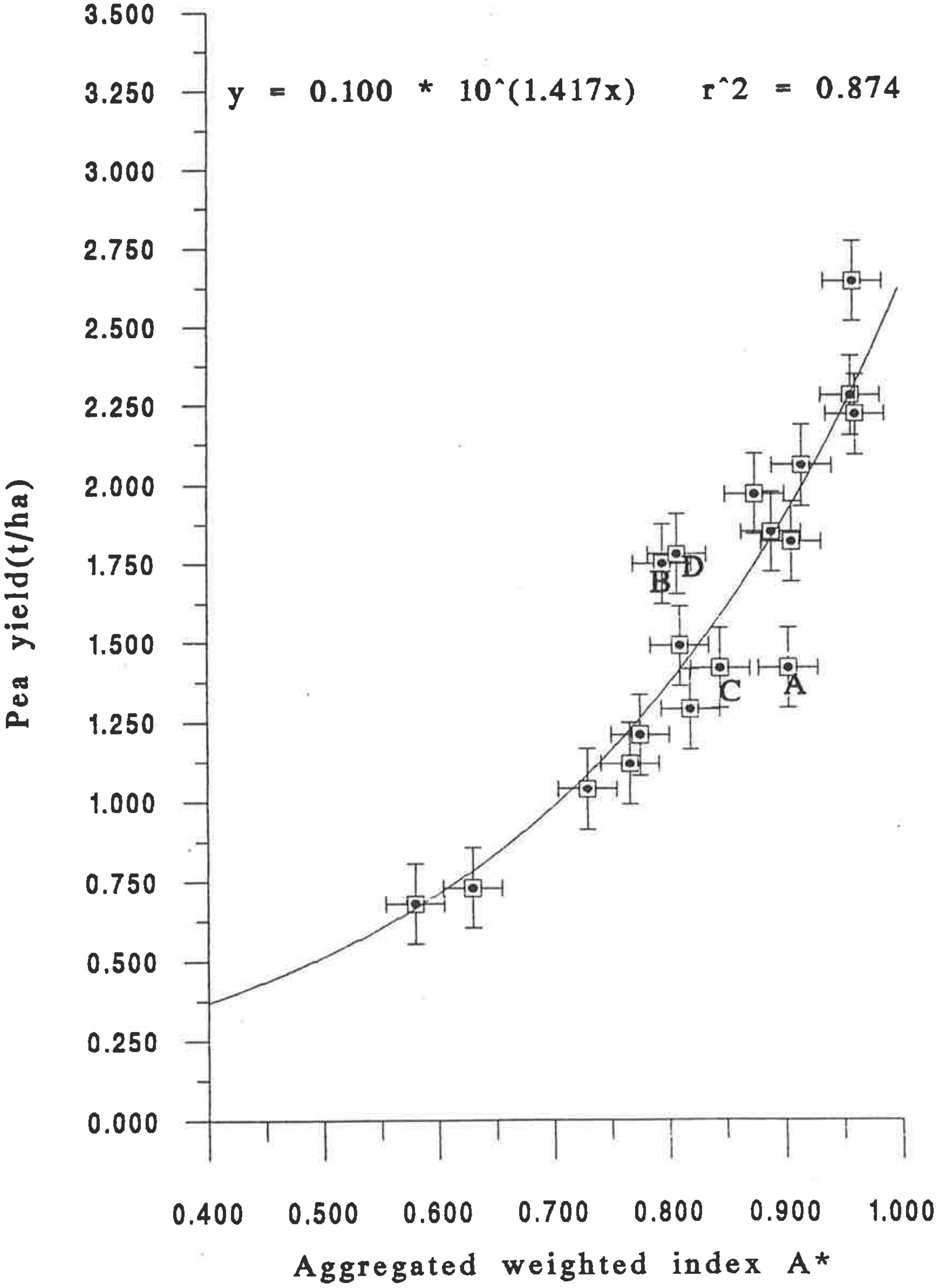
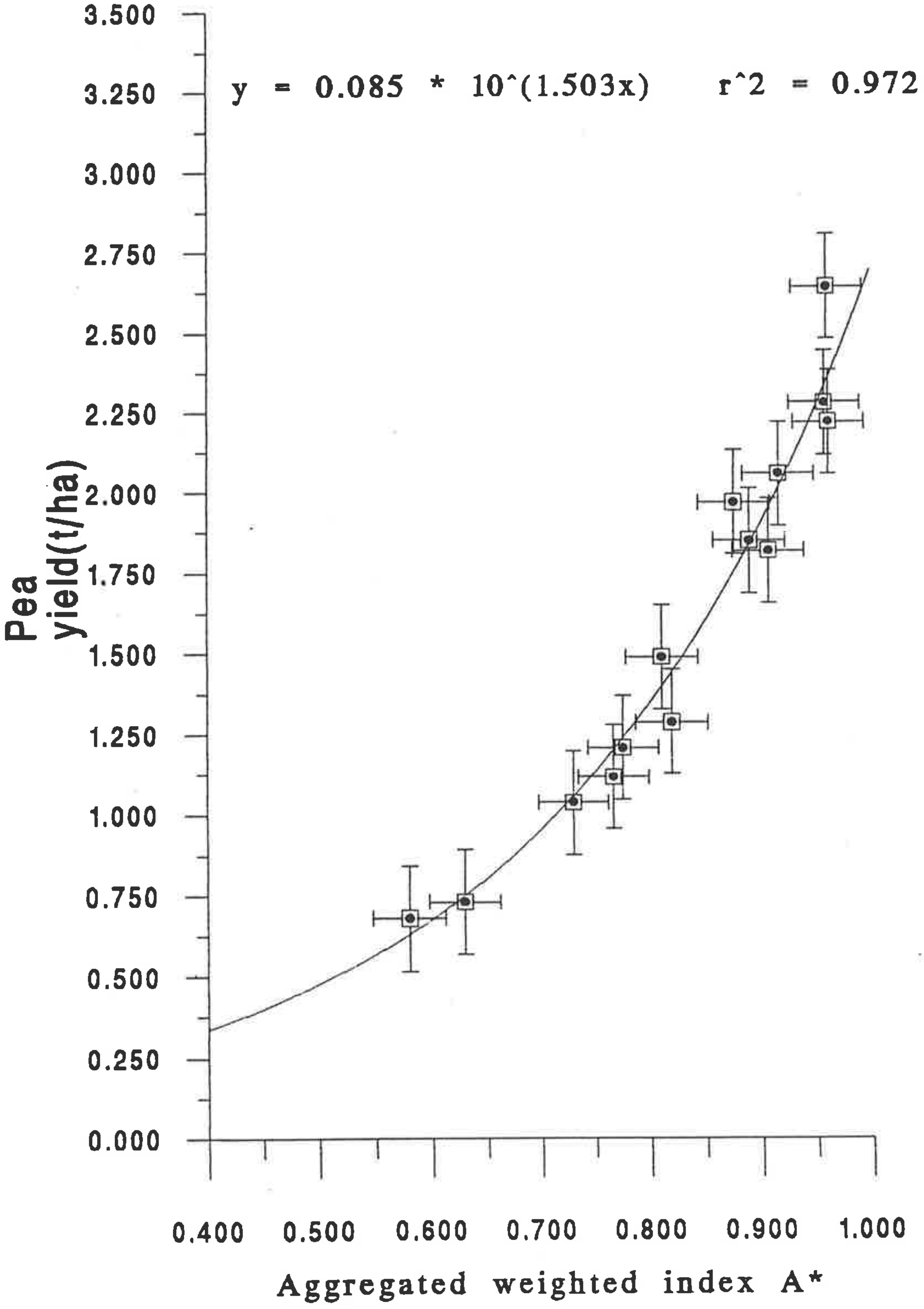


fig 4.7 Pea yield plotted against the aggregated weighted index with outriders omitted. Based on expert weightings



This indicates that a weighting of around 0.5 for both climate and soil variables is most appropriate to the variables studied.

5 Conclusion

The aggregated knowledge model gives a computational framework for dealing with complex interactions which have not (or cannot) be related experimentally. In deriving the weighted sets, we have used expert knowledge. The result shows the model incorporating expert knowledge can be used to predict pea yields. The results are however limited to the study of crops.

The technique provided a mechanism for analysing datasets that are incomplete. In addition, when empirical data do not fit the membership function, the explanations offered for outriders provided a sound knowledge acquisition strategy. For example, in fig 4.6, values from trial sites A, B, C and D indicated variance with the expected yield membership function constructed from climatic and soil variables. The reasons given for these outriders are presented in table 4.4. From a knowledge acquisition view, outriders such as in A, B, C and D provide an interesting basis on which to focus discussion on exceptional or unusual cases. The explanations for the outriders define the boundaries of domain knowledge. Their explanation requires expert intervention and they can be used to elicit knowledge-base rules (Kirkby 1993).

The type of knowledge-incorporated-analysis described here could be used to consider the combined effect of variables which cannot be related in quantitative terms, e.g. the effect of type and level of management and the environmental effects of different land management practices. In particular, its main value is to incorporate user and experimental knowledge in an aggregated way. This aggregation provides a methodology for experimenting with the effects of a given variable, or groups of variables, on the overall outcome of the system. In this case, the system outcome can be directly measured in terms of crop yield predictability and provides a quantitative assessment of the data validity.

Chapter 5. Comprehensive Evaluation Model

Environmental Effects of Agriculture

The method of incorporating aggregated knowledge and fuzzy membership construction can be used in constructing a comprehensive evaluation model. The work described here gives an example of the method in which both empirical and land-user knowledge can be combined. The model uses fuzzy sets which are integrated in an interaction matrix. This gives a numerical value which is a measure of the comprehensive effects of all the factors considered on environment. It gives a method by which the knowledge of farmers and land managers can be integrated. The work addresses the need for managers to have a way of assessing how many factors could interact to give an end result.

5.1 Introduction

Fuzzy logic can describe a system by using "commonsense" rules that refer to definite quantities (Kasko and Isaka,1993). This work describes an example of how the environmental effects of cropping and associated management practices could be assessed by fuzzy interaction matrices in an integrated way.

The effects considered are: (1) soil degradation; (2) water pollution; and (3) soil erosion. The management practices considered were: (1) Cultivation intensity; (2) Stubble retention; (3) Type of crops; (4) Rotation history; (5) Level of fertiliser input, (6) Extent of erosion management; and (7) Type of tillage.

The model has been developed in response to the need to apply what we know in an effective integrated comprehensive way as an aid to managing our land resources in a non-polluting and sustainable way.

5.2 Methodology

A comprehensive rule based and fuzzy interaction matrix was used to determine the effect of the interaction of management practices with the following land characteristics: slope, soil texture, depth of soil, proximity to drainage lines, soil permeability, soil nutrient level, soil cover together with rainfall intensity and amount to give estimates of erosion, soil degradation and water pollution. These were integrated to give an overall assessment of environmental impact.

5.2.1 Matrix Formulation

The structure of the interactive matrix was similar to equations 2.1 and 3.1

$$\begin{pmatrix} W_1 & W_2 & W_3 \end{pmatrix} \begin{pmatrix} \begin{pmatrix} W_{d1} & W_{d2} \end{pmatrix} \begin{pmatrix} D_{d1} \\ D_{d2} \end{pmatrix} \\ \begin{pmatrix} W_{p1} & W_{p2} \end{pmatrix} \begin{pmatrix} D_{p1} \\ D_{p2} \end{pmatrix} \\ D_e \end{pmatrix} = C \qquad (5.1)$$

Where:

- D_{d1} and D_{d2} = Degree of membership for cultivation intensity and nutrient removed, respectively. Subscript d standing for soil degradation.

- D_{p1} and D_{p2} = Degree of membership of fertilizer input and pesticide use, respectively. Subscript p standing for water pollution.

- D_e = Degree of membership of erosion for various crops and associated management practices.

- W_{d1} and W_{d2} = Weightings for relative importance of cultivation intensity and nutrient removal on soil degradation.

- W_{p1} and W_{p2} = Weightings for the relative importance of fertilizer and pesticide input on water pollution respectively.

Overall weightings

- W_1, W_2, W_3 are the weightings for the influence of soil degradation, water pollution and soil erosion on C.

- C = the comprehensive environmental effects index.

5.2.2 Weighting Determinations

Where empirical values could be found, they were used to determine weightings. Otherwise, a system of expert weightings was used, by assigning weights to variables to express their relative interactive importance to each other in a way as described in the introduction (section 4.3).

5.2.3 Degree of Membership Determinations

(i) Cultivation Intensity (D_{d1}).

This was provided by the user (eg farmer) following consultation for various crops (Table 5.1).

Table 5.1 Membership degree for Cultivation or pesticide use intensity on soil degradation or water pollution.

Cultivation or pesticide use intensity	Very high	High	Average	Low	Very low
Graded membership	1.0	0.8	0.6	0.4	0.2

(ii) Nutrient removal (D_{d2})

For this determination, the inherent level of the soil nutrition was considered. The user was asked to give the qualitative nutritional level for N, P&K of the soil, according to Table 5.2.

Table 5.2 Constants for soil nutrient deficiencies

NUTRIENT DEFICIENCY (IES)			constants FOR N P K		
N	P	K	N	P	K
x			0.4	0.1	0.1
	x		0.1	0.4	0.1
		x	0.1	0.1	0.4
x	x		0.4	0.4	0.1
	x	x	0.1	0.4	0.4
x		x	0.4	0.1	0.4
			0.1	0.1	0.1
x	x	x	0.4	0.4	0.4

* x in the table represent the nutrient deficiencies.

This was combined with the extent of nutrient removal by the crops considered as (Table 5.3).

Table 5.3 Graded Membership for Nutrient removal by crops of good average yield

Crop	Removal of N(kg/h)	Graded Member-ship	Removal of P (kg/h)	Graded Member-ship	Removal of K (kg/h)	Graded Member-ship
Wheat (summer)	147	0.66	67	0.72	82	0.91
Wheat (winter)	150	0.67	70	0.75	70	0.16
Barley	125	0.56	56	0.60	79	0.18
Oats	115	0.51	59	0.63	107	0.24
Beans	176	0.79	24	0.26	80	0.18
Pea	150	0.67	very small	0.1	very small	0.05
Sunflower	87	0.39	75	0.81	75	0.17
Sugar Beet	200	0.89	82	0.9	288	0.65
Potatoes	215	0.96	83	0.9	443	1.0
Kale	224	1.0	67	0.72	202	0.46

* *Modified from Lockhart and Kliseman (1988)*

The degree of membership for nutrient remove can be determined by equation 5.2

$$D_{d2} = C_N D_N + C_p D_p + C_k D_k \qquad (5.2)$$

Where:

- D_N, D_P and D_K are the Degrees of Membership for the N, P and K removed by a given crop respectively.

- C_N, C_P and C_K are constants for the levels of N, P and K in the soil. These can be obtained from Table 5.2.

(iii) Fertilizer Input (D_{p1})

The degree of graded membership was determined by asking the user for the intensity of fertilizer input for each crop with reference to Table 5.4

Table 5.4 Graded Membership for Fertilizer Input on Water Pollution

Fertilizer input intensity (kg/h)	<50	50-100	100-200	200-300	300-400	>400
Graded Membership	0.1	0.2	0.4	0.6	0.8	1

(iv) Level of Pesticide Use (D_{p2})

This was obtained by asking the user if their level of use was "very high", "high", etc. where the degree of membership for these ratings are the same as in Table 5.1.

(v) Erosion (D_e)

These were obtained by reference to typical values for soil loss given in Table 5.5 for various crops (Morgan,et al, 1982).

Table 5.5 Grade Membership for Type of Crop on Erosion

CROP	GRADED MEMBERSHIP
Wheat or rice	0.1
Barley or Oats	0.1
Pea and Beans	0.2
Sunflower	0.4
Sugar beet	0.3
Potatoes	0.3
Grass	0.01
Woodland	0.002
Bare Soil	1.00

Summarized from Morgan (1986)

5.2.4 Weightings

(i) Weightings for cultivation intensity (Wd_1) and nutrient removal (W_{d2}): These were considered equally important in determining soil degradation and weighed accordingly (0.5: 0.5).

(ii) Weighting for fertilizer input (W_{p1}) and amount of pesticide use (W_{p2}): Pesticides were considered more important as a pollutant from human considerations, and received a weighting of 0.7 compared with 0.3 for fertilisers.

5.2.5 Overall Weightings

(i) Soil degradation (W_1)

This was obtained from a sub-matrix

$$\left(w_R w_S w_C\right)\begin{pmatrix} D_R \\ D_S \\ D_C \end{pmatrix} = W_1 \qquad (5.3)$$

Where D_R = Degree of membership for the rotation history. This is given in Table 5.6 obtained from the results of Schultz (1988).

Table 5.6 Graded membership for rotation history* on soil degradation

Rotation	Pasture (legume medic)	Vetch	Beans	Lupins	Peas	Fallow	Cereal
Graded Membership	0.0	0.1	0.25	0.3	0.4	0.5	1.0

**Summarised from Fig 1, of Schultz (1988)*

- D_S = Degree of membership for the amount of stubble retention is given in Table 5.7.

Table 5.7 Graded membership for the amount of stubble return on soil degradation

Stubble Return (T/ha)	0	1	2	3	4	5
Graded Membership	1	1.08	0.6	0.4	0.2	0

- D_C = Degree of membership for the type of crop considering legumes = 0.3 and non-legumes = 0.7

- W_R ,W_S and W_C are weightings for rotation history, extent of stubble return and type of crop, respectively. They estimate, with respect to each other, their relative effects on soil degradation. The values chosen were 0.5, 0.3 and 0.2, respectively.

The relative importance of these weightings can be varied to suit different management and cropping practices.

(ii) Water Pollution (W_2)

This was determined from a sub-matrix:

$$\left(W_{pd} W_{dg} W_{rfi} W_{sp}\right) \begin{pmatrix} D_{dp} \\ D_{dg} \\ D_{rfi} \\ D_{sp} \end{pmatrix} = w_2 \qquad (5.4)$$

Where:

- D_{dp} is the degree of graded membership for proximity to drainage lines and is given in Table 5.8.

Table 5.8 Graded Membership for proximity to drainage lines on water pollution

Proximity to drainage line (m)	<100	100-200	200-300	300-400	400-500	500-600	>600
Grade Membership	1	0.7	0.5	0.4	0.3	0.2	0.1

Derived from Thomas & Bennett (1987)

- D_{dg} is the degree of graded membership for proximity depth to ground water. These are given in Table 5.9.

Table 5.9 Graded Membership for Depth to Ground Water on Water Pollution

Depth of Ground Water (m)	<0.5	0.5-1	1-1.5	1.5-2.5	2.5-3	3-4	4-5	>5
Grade Membership	1	0.9	0.6	0.4	0.3	0.2	0.1	0

Derived from Thomas and Bennett (1987)

- D_{rfi} is the degree of graded membership for rainfall intensity. This is given in Table 5.10.

Table 5.10 Graded membership for rainfall intensity

Rainfall	Intensity (mm/hr)	Grade Membership
Drizzle	0.25	0
Light rain	1.02	0.1
Moderate rain	3.81	0.2
Heavy rain	15.24	0.4
Excessive rain	40.64	0.6
Cloud-burst	101.6	1

From Lull, 1959

- D_{sp} is the degree of graded membership for soil permeability. These are given in Table 5.11.

Table 5.11 Grade membership for soil permeability on water pollution*

SOIL	PERMEABILITY	GRADE MEMBERSHIP
Clay and clay loam	Very slow	0.2
Silt and Silty clay loam	slow to moderately slow	0.3
Sandy loam	Moderately slow to rapid	0.7
Sandy	Rapid	1

* Modified from Beauchamp (1955)

- W_{pd}, W_{dg}, W_{rfi} and W_{sp} are estimates of the relative importance of proximity to drainage lines, depth to ground water, rainfall intensity and soil permeability to one another. These can be estimated using the weighting table, Table 5.1.

(iii) Soil Erosion (W_3)

The soil erosion sub--matrix was constructed as follows:

$$\left(W_{eh} W_{ifi} W_{sd} W_{em}\right)\begin{pmatrix} D_{eh} \\ D_{rfi} \\ D_{sd} \\ D_{em} \end{pmatrix} = W_3 \qquad (5.5)$$

Where:

D_{eh} =Degree of membership for erosion hazard given in Table 5.12.

Table 5.12 Graded Membership of soil characteristic on Erosion Hazard

Graded Membership	SURFACE SOIL	SAND TO LOAMY SAND		SANDY LOAM TO LOAM		CLAY LOAM & SILTY CLAY LOAM		SILTY CLAY & CLAY
	Soil Permeability (cm/hr)	<6.4	>6.4	<2.0	>2.0	<0.5	>0.5	Any
	Erosion Hazard	% slope	% slope	% slope	% slope	% slope	% slope	% slope
0	None	0-2	0-2	0-2	0-2	0-2	0-2	0-2
0.3	Slight	2-9	2-5	2-9	2-5	2-9	2-5	2-9
0.5	Moderate	9-15	5-9	9-15	5-9	9-15	5-9	9-15
0.7	Severe	15-30	9-15	15-30	9-15	15-30	9-15	15-30
1	Very Severe	30 plus	15 plus	30 plus	15 plus	30 plus	15 plus	30 plus

**Adapted from Thomas & Bennett (1987)*

- D_{sd} = Degree of membership for soil depth which can be obtained by reference to Table 5.13.

- D_{em} = Degree of membership for erosion management. These are given in Table 5.14.

Table 5.13 Graded Membership for tillage intensity and stubble cover on soil erosion

Soil Depth (m)	<0.5	0.5-1	1-2	2-3	3-4	4-5	>5
Grade Membership	1	0.9	0.8	0.6	0.4	0.3	0.2

Table 5.14 Graded Membership for tillage intensity and stubble cover on soil erosion

Stubble Cover (T/ha)	Tillage Intensity				
	Very High	High	Average	Low	Very low
0	1	0.8	0.7	0.6	0.5
1	0.8	0.7	0.6	0.5	0.4
2	0.7	0.6	0.5	0.4	0.3
3	0.6	0.5	0.4	0.3	0.2
4	0.5	0.4	0.3	0.2	0.1
5	0.4	0.3	0.2	0.1	0

Adapted from Malinda et al (1990)

W_{eh}, W_{rf} , W_{sd} and W_{eh} are weightings for the relative importance of erosion hazard, rainfall intensity, soil depth and erosion management on soil erosion.

These were weighted with reference to Table 1.

5.3 Discussion

The basis for this work has been well summarized by Smiles (1992) in that management decisions will inevitably be made with inadequate information combined with a good deal of commonsense. The methodology described provides a means by which both empirical and land user knowledge can be combined to give a numerical assessment of the effects of many variables on the environment. It enables the integration of knowledge in close collaboration with farmers and other land users. It also addresses the critical need for a practical interdisciplinary way to understand systems and solve problems in land management (Pesek 1989).

We are dealing with a very complex system and it is likely that we will never have sufficient information on such a dynamic and multivariate interacting system to provide exact solutions (Thomas and Bennett, 1987). However, workable solutions may be possible by the use of human commonsense knowledge. Fuzzy set theory deals with formalizing commonsense and reasoning (Zadeh,1983). Fuzzy sets mathematically describe the way we visualize, from the information available, how a system behaves. The grade of membership gives a measure of the degree to which a variable effects a process. Weightings give a measure of the way in which the variables considered interact with each other to effect processes and the overall result, which is the comprehensive environmental effects index in this case. Changing the weightings provides a means of experimenting to evaluate the importance of a variable in determining the overall result. Experimenting with the weighting values also gives us a means of learning how a system might behave under changing conditions. The data we have used and the weightings given are but examples. Locally more appropriate data and weightings can always be used.

Chapter 6

A Fuzzy Comprehensive Evaluation Model For Decision Making in Crop selection

The method described gives a means of integrating knowledge into a numeric formulation using fuzzy sets which are combined into interaction matrices. The knowledge can come from many sources and disciplines.

The method has wide application as an aid to decision making. It can be used to consider various input conditions and allows for flexible treatment of the variables considered. The example given here considers four sections in the decision making process for crop selection. The sections are: climate and soil; economic conditions; management ability; and environmental impacts. In each section a first level evaluation is made based on graded membership of the variables in each section. The relative importance of each variable compared to each other can be weighted either from experimental information or human (expert) experience. These are combined in interaction matrices to obtain first level evaluation vectors for each section. These section vectors are then combined into an overall interaction matrix to obtain a numeric end result. This will be demonstrated by considering how to select the most suitable crop for cultivation. This work demonstrates the way the method can be organized by way of an example. It is considered that the method described could be used as a foundation for rule acquisition in computerized machine learning.

6.1 Introduction

Decision making usually requires a consideration of the interplay of many variables. Knowledge of these variables can come from many sources and disciplines. It can come from experimental work together with that acquired by human observations and experience. To make decisions, this information and knowledge has to be brought together and analyzed. The analysis, after taking all considerations into account, should reach a comprehensible result which can be used in decision making.

The method described gives a generic way of integrating knowledge and information into a numeric formulation. This gives an assessment of the interplay of the interactions considered and reaches comprehensive evaluation. It has a wide range of application in many fields. This work gives an example of the method in a comprehensive evaluation for crop selection.

Land managers have to make decisions on the interaction of a wide range of considerations e.g. biophysical land capability (climate and soil), economic, management ability, environmental effects and personal preference and goals. Land managers need a synthesis of this information to help reach his conclusions. This is done here using fuzzy set in an interaction matrix.

6.2 Method

6.2.1 Comprehensive Evaluation

Assume the object set $C = \{C_1, C_2, \ldots, C_p\}$ and the object's attribute set $X = \{ x_1, x_2, \ldots, x_m\}$. Given the grade membership of each object to each attribute:

$$C_{xj}(Ci) = r_{ij} \qquad r \in [0, 1]$$

Then the Fuzzy Relationship Matrix of C to X is:

$$\underline{R} = \begin{array}{cc} & \begin{matrix} C_1 & C_2 & \dots & C_p \end{matrix} \\ \begin{matrix} x_1 \\ x_2 \\ \cdot \\ x_m \end{matrix} & \begin{pmatrix} r_{1,1} & r_{1,2} & \dots & r_{1,p} \\ r_{2,1} & r_{2,2} & \dots & r_{2,p} \\ \dots & \dots & \dots & \dots \\ r_{m,1} & r_{m,2} & \dots & r_{m,p} \end{pmatrix} \end{array} \qquad (6.1)$$

If weightings are given to each attribute, a fuzzy set or a fuzzy vector on X is given by

$$A = \{ a_1, a_2, \dots, a_m \} \qquad (6.2)$$

where $\sum_{i=1}^{m} a_i = 1 \quad (0 \leq a_i \leq 1)$

The Comprehensive evaluation result $\underline{B}$ is:

$$\underline{B} = \underline{A} \, o \, \underline{R}$$

Where $\underline{B}$ is a fuzzy set on C, and $\underline{B} = (b_1, b_2, \dots bp)$. The optimal object should be $B^* = \max(b_1, b_2, \dots b_p)$.

The operation of the Matrix $\underline{A}$ o $\underline{R}$ can be operated in the following way (Wang 1983)

$$b_j = \bigvee_{i=1}^{n} (a_i \wedge r_{ij}) \qquad (6.3)$$

$$b_j = \bigvee_{i=1}^{n} (a_i \cdot r_{ij}) \qquad (6.4)$$

$$b_j = \sum_{i=1}^{n} (a_i \wedge r_{ij}) \qquad (6.5)$$

$$b_j = \sum_{i=1}^{n} (a_i \cdot r_{ij}) \qquad (6.6)$$

Model (6.3) is a primary factor determination type. The primary factor determines the result.

Model (6.4) and (6.5) highlight the primary factor and also consider secondary factors.

Model (6.6) is a model with no primary or secondary factors, but considers all factors according to their weightings..

These four models can be used to calculate a result in different situations. The more the agreement between the models, the greater the confidence in the result.

6.2.2 Fuzzy Multi-level Comprehensive Evaluation

In a complicated system, many variables need to be considered in the way they influence a final outcome. Such variables may also exist at several levels of influence. If we evaluate all these variables at one level, the weightings given to each variable are difficult to assign because: 1) it is easier for the human mind to deal in small groups of variables; 2) the weighting set A must satisfy the condition $\sum_{i=1}^{m} a_i$ ($0 \le a_i \le 1$) and 3) the compound operation in the fuzzy matrix may be given by taking the maximum or minimum value (relation 6.3, 6.4, 6.5). If the number of variables is large, the weightings are small, hence they dominate the grade membership in the matrix. In this way, the final evaluation loses its significance. To counter this situation, a multi-level comprehensive evaluation model can be formulated (Chen 1983).

The principle of multi-level comprehensive evaluation model is to divide the variables according to their properties into sets. The evaluation of each set is termed a first level comprehensive evaluation. This is to obtain the first level evaluation vectors for each set. The next evaluation level is to combine these vectors in a relationship matrix. This matrix operates the overall weighting set associated with each vector to obtain a multi-level comprehensive evaluation.

The process of formulating a multi-level evaluation model is:

- To a given set X, if C is one of n elements on X and satisfies the relation

$$\bigcup_{i=1}^{n} x_i = X$$

$$x_i \cap x_j = \phi \quad , \qquad i \neq j$$

then C is one division to X. The division set of C on X can be assigned as:

$$X/\mathrm{C} = \{ X_1, X_2, \ldots, X_\mathrm{n} \} \quad X_i = \{X_{ik}\}, \qquad i = 1,2,\ldots n \text{ and } k=1,2,\ldots m$$

where X_i has K_i factors and X has $\sum_{i=1}^{n} k_i$ factors.

- Assume the object set $\mathrm{C} = \{\mathrm{C}_1, \mathrm{C}_2, \ldots, \mathrm{C}_\mathrm{p}\}$. The first level comprehensive evaluation on each X_i with k_i factors proceeds as follows. Suppose the weighing assigned to X_i factors is a vector $\underline{\mathrm{A}}_i$, the relationship evaluation matrix is $\underline{\mathrm{R}}_\mathrm{i}$, the first level comprehensive evaluation vector is:

$$\underline{\mathrm{B}}_i = \underline{\mathrm{A}}_i \circ \underline{\mathrm{R}}_i = (\mathrm{b}_{\mathrm{i}1}, \mathrm{b}_{\mathrm{i}2}, \ldots, \mathrm{b}_{\mathrm{ip}})$$

- The multi-level comprehensive evaluation model $\underline{B}$ is given by the interaction matrix

$$\underline{B} = \underline{A} \circ \underline{R} = \underline{A} \circ \begin{pmatrix} B_1 \\ B_2 \\ \vdots \\ B_i \\ \cdots \\ B_n \end{pmatrix} = (b_1 \ b_2 \ \ldots \ b_p) \qquad (6.7)$$

Where $\underline{A}$: is overall weighting set for factor sets of B, and $\underline{R}$: is relationship matrix combined from the first comprehensive evaluation vectors: B_1, B_2, $\ldots B_n$. The Optimal object should be $\underline{B}^* = \max(b_1, b_2, \ldots, b_p)$

6.3 Crop selection

To select the most suitable crop for a parcel of land, the biophysical, economic (gross margin), management ability together with the social and environmental impacts are considered. This selection can be done using the Fuzzy multi-level comprehensive evaluation model.

Suppose we have five crops to chose from,

$$C = (C_1, C_2, \ldots C_5),$$

We can do the first level evaluations of the suitability of these five crops in terms of the above considerations respectively.

6.3.1 Biophysical evaluation

Chater 3 and 4 demonstrated that yield determinations could be made using climate and land variables in an interactive matrix of the form:

$$\begin{pmatrix} Wc & Ws \end{pmatrix} \begin{pmatrix} \begin{pmatrix} Wc_1 & Wc_2 \ldots Wc_n \end{pmatrix} \begin{pmatrix} Dc_1 \\ \vdots \\ Dc_n \end{pmatrix} \\ \\ \begin{pmatrix} Ws_1 & Ws_2 \ldots Ws_m \end{pmatrix} \begin{pmatrix} Ds_1 \\ \vdots \\ Ds_m \end{pmatrix} \end{pmatrix} = A^* \qquad (6.8)$$

Where:

D_{C1}, D_{C2},..., D_{Cn} = graded membership for climate variables.

W_{C1}, W_{C2},...,W_{Cn} = weightings given to each climatic variable with respect to the importance of each compared to each other where $\sum_{i=1}^{N} W_{Ci} = 1.0$

D_{S1}, D_{S2}, ...,D_{Sm} = graded membership of the soil variables.

W_{S1}, W_{S2},...,W_{Sn} = weightings given to each soil variable with respect to each other, where

$$\sum_{i=1}^{m} W_{Si} = 1.0$$

Wc = comprehensive climate weighting.

Ws = comprehensive soil weighting.

A* = aggregate weighted index.

This matrix can also be regarded as a comprehensive evaluation of soil and climate suitability for a given crop(k). The A* can be considered as a biophysical suitability index for this crop.

Fig.6.1 is a general plot of crop yield against A* obtained by Sun et al(1993 a&b):

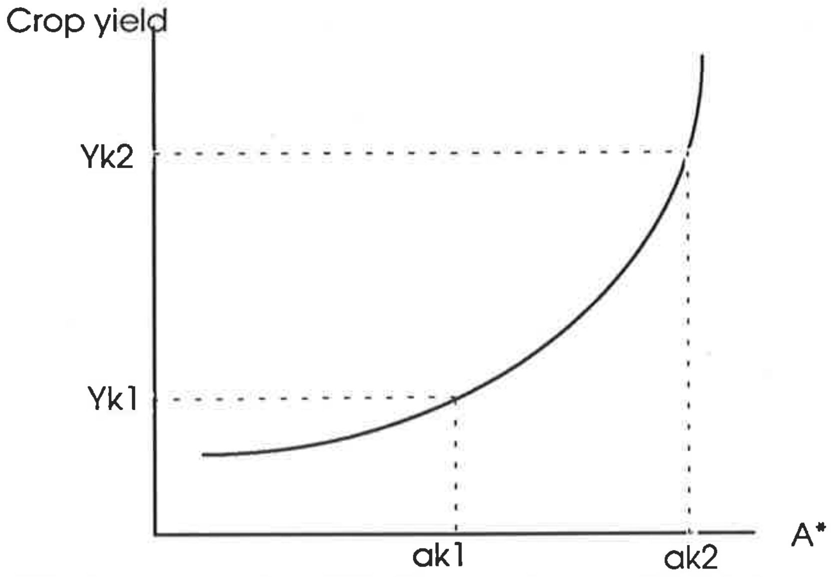


Fig 6.1 Crop yield against aggregated weighting index(A*)

From Fig 6.1 the user is asked for their desired yield (**Yk2**) and the' break even economic yield' (**Yk1**) for crop k, then the corresponding values of A* (**ak2** and **ak1**) can be obtained from fig 6.1.

Then the membership function of biophysical suitability for crop k can be expressed:

$$D_{Bk}(A^*) = \begin{cases} 0 & A^* \leq \mathbf{ak1} \\ \dfrac{A^* - \mathbf{ak1}}{\mathbf{ak2} - \mathbf{ak1}} & \mathbf{ak1} < A^* < \mathbf{ak2} \\ 1 & A^* \geq \mathbf{ak2} \end{cases} \quad (6.9)$$

where $D_B(A^*)$ is the degree of membership for a given crop.

From this approach we could set up membership functions for these five crops, then the biophysical evaluation vector D_B of these five crops is:

$$B_B = [D_{B1}(A^*), D_{B2}(A^*), \ldots, D_{B5}(A^*)]. \quad (6.10)$$

6.3.2 Economic (gross-margin) evaluation

In a similar way, the economic vector can be obtained from the economic membership functions for these five crops.

The yields of these five crops for a given parcel of land can be estimated by determining A* from relation (6.8). The gross margin (G) for a given crop(k) can be obtained from the prices return of the yield minus the fixed and variable costs. For a given crop(k), suppose G_{1k} and G_{2k} are the gross margin associated with the 'break even' yield and the 'desired' yield. Then the membership function for economic evaluation of crop k could be expressed :

$$D_{ck}(G) = \begin{cases} 0 & G \le G_{1k} \\ \dfrac{G - G_{1k}}{G_{2k} - G_{1k}} & G_{1k} < G < G_{2k} \\ 1 & G \ge G_{2k} \end{cases} \qquad (6.11)$$

Using the same method we can derive membership functions for the economic evaluation of the 5 crops. The economic evaluation vector B_c is:

$$B_c = [\, D_{c1}(G), D_{c2}(G), \dots, D_{c5}(G) \,]. \qquad (6.12)$$

6.3.3 Management ability evaluation

Suppose the farmer's management ability for these five crops is determined by three criteria:

- Level of education (M_1);
- Information availability (M_2);
- Experience (M_3).

Given the weightings assigned for these three criteria are,

$$A_m = (a_{m1}, a_{m2}, a_{m3}).$$

The Fuzzy relationship Matrix:

$$R_m = \begin{array}{cc} & \begin{array}{cccc} C_1 & C_2 & \dots & C_5 \end{array} \\ \begin{array}{c} M_1 \\ M_2 \\ M_3 \end{array} & \begin{pmatrix} r_{11} & r_{12} & \dots & r_{15} \\ r_{21} & r_{22} & \dots & r_{25} \\ r_{31} & r_{32} & \dots & r_{35} \end{pmatrix} \end{array} \qquad (6.13)$$

Where r_{ij} is the degree to which crop C_i is affected by management criteria m_i.

Then the management evaluation vector B_m for these five crops is,

$$B_m = A_m o\, R_m = (B_{m1}, B_{m2}, \dots, B_{m5}), \qquad (6.14)$$

The weighting set and r_{ij} can be obtained using human information in a hierarchic table which was described in Introduction IV.III.

6.3.4 Environmental impact evaluation

Suppose there are three aspects which determine the environmental impacts of the crops considered:

- Soil Degradation (E_1);
- Soil Erosion (E_2);
- Pollution (Soil and water) (E_3).

The weighting set for these three aspects is $A_E = (a_{E1}, a_{E2}, a_{E3})$.

For a given crop k the weighted intensity index for soil degradation (reference to Fig 6.2) can be determined by,

$$D_{k1} = (W_c, W_n)\begin{pmatrix} D_{kc} \\ D_{kn} \end{pmatrix}. \qquad (6.15)$$

Where W_c and W_n are the weightings for the effect of cultivation intensity and nutrient removal respectively on soil degradation.

D_{kc} and D_{kn} are the degrees of membership for the effect of cultivation intensity and nutrient removal respectively on soil degradation.

Using the same approach we could get weighted intensity index of soil erosion and pollution (D_{k2}, D_{k3}) for a given crop k. This is outlined in Fig 6.2. The higher the D_{kj} the greater the negative environmental effects. Therefore the fuzzy relationship matrix for these five crops is:

$$R_E = \begin{array}{cc} & \begin{array}{ccc} C_1 & \cdots & C_5 \end{array} \\ \begin{array}{c} E_1 \\ E_2 \\ E_3 \end{array} & \begin{pmatrix} 1-D_{11} & \cdots & 1-D_{51} \\ 1-D_{12} & \cdots & 1-D_{52} \\ 1-D_{13} & \cdots & 1-D_{53} \end{pmatrix} \end{array} \tag{6.16}$$

Then the environmental impact evaluation vector B_E is:

$$B_E = A_E \circ R_{E.} \tag{6.17}$$

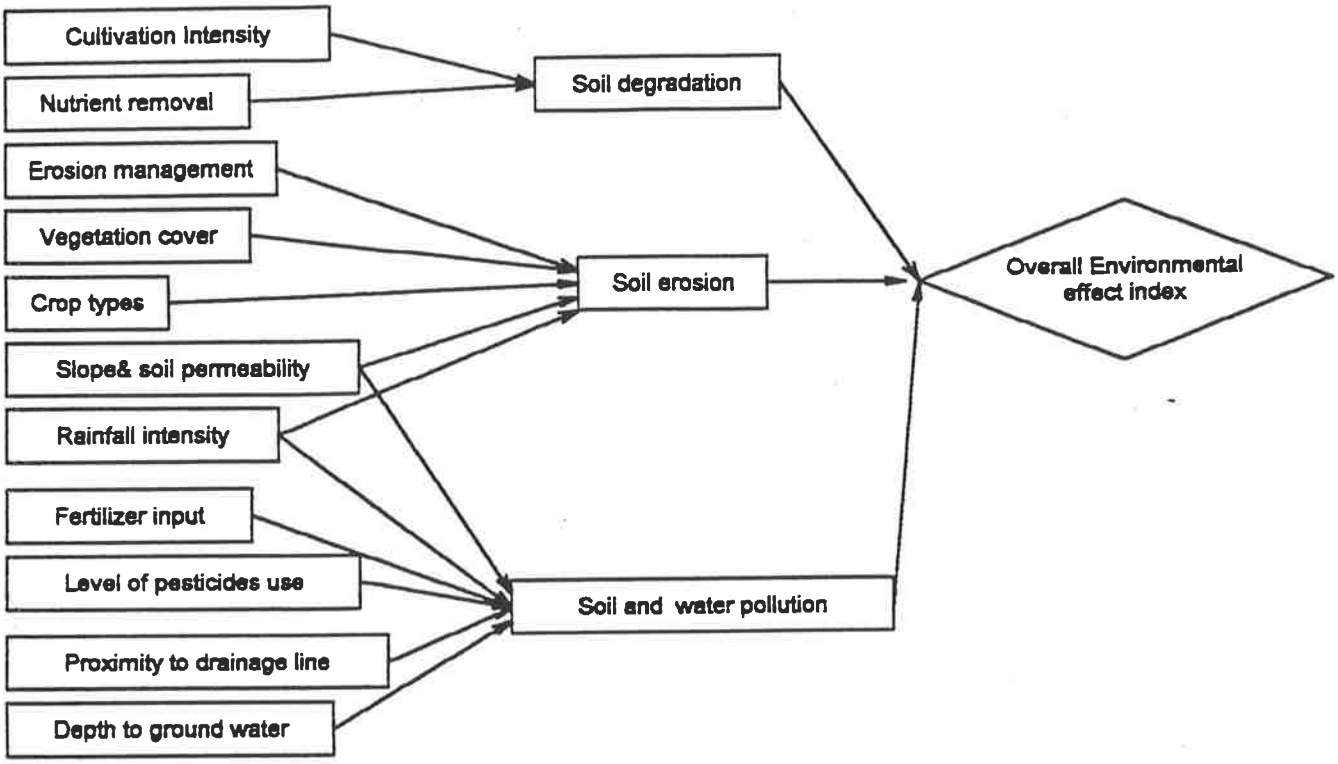


Fig 6.2 Interactions considered in determining the environmental effects of growing various crops to give an overall environmental effects index

6.3.5 Multi-level comprehensive evaluation

Combining the vectors obtained from each section above (relation 6.10, 6.12, 6.14, 6.17). The multi-level comprehensive evaluation model $\underline{B}$ for crop suitability is:

$$\underline{B} = \underline{A} \circ \underline{R} = \underline{A} \circ \begin{pmatrix} B_b \\ B_c \\ B_m \\ B_E \end{pmatrix} = (b_1 \ b_2 \ b_3 \ b_4 \ b_5). \qquad (6.18)$$

Where $\underline{A}$ is the overall weighting about the relative important of the four sections: biophysical, economic, management ability and environmental impact.

b_1 , b_2 , b_3 , b_4 and b_5 are the comprehensive evaluation values for these five crops, and the most suitable crop is obtained by max ($b_1 \ b_2 \ b_3 \ b_4 \ b_5$).

6.4. Discussion

The comprehensive evaluation methods described here provides a means of combining interdisciplinary knowledge gained from experience, observation and experiment in a comprehensive numeric way. This results in an estimate of how various considerations affects an end result.

The development of methods such as this is important as they give us a computational framework for dealing with : (1) complex interactions which have not or cannot be related experimentally; (2) data sets that always remain incomplete; (3) information that comes from a range of disciplines and sources.

In the foreseeable future, it seems that we will have to make management decisions by combining experimental information with human knowledge and experience. This is because we have to deal with experimental information from many sources which is inadequate and difficult to integrate. The method described here can incorporate human knowledge and experience with existing experimental information.

In this method the manager/ user, by way of the weightings, can estimate how the interplay of various practices could affect their goals, especially in the socio-political and management aspects in which no experimental data exists.

This ability to make an active contribution to the decision making process should help in the user's comprehension of the systems being dealt with. Through this interaction , a continual dynamic adjustment of the weightings could be made. Means whereby weighting adjustments could be made would be aided by developments in automated rule acquisition using symbolic machine learning techniques.

Conclusions

The development of a method of the type that has been described in this thesis can overcome the shortcoming of conventional parametric methods which lack the ability to deal with: 1) complex interactions between variables which have not or cannot be related experimentally; 2) inadequate and/or incomplete data sets; and 3) incorporate user knowledge, which is expressed in natural language and often contains uncertainty, into models so that decision can be made based upon both objective and subjective information.

The use of a multiplicative parametric method to estimate land capability for dry land agriculture and grazing in Fukang County of China revealed that a parametric method was reasonably successful in predicting plant production and hence land capability. However, it did show that a more interactive way of dealing with the operative variables would be of great advantage. The method can only be used if the data sets are available and complete.

Here a new model using fuzzy sets constructed into an interaction matrix was used. In the interaction matrix the variables are weighed and summed in the way they affect a result. In this case the way rainfall and soil variables affect the availability of water to plants and hence influence rangeland productivity. This increases the predicability of production to 81% compared to models using rainfall alone and a multiplicative parametric model which gives predicability of 61% and 67%. respectively. The results also showed that: 1) rainfall was most important in determining production at lower rainfalls <350 mm; 2) soil texture and particularly slope were important throughout the rainfall range, 149mm-700mm, investigated; and that 3) soil depth was only important at the higher >350mm rainfalls.

This new method indicated the potential ability to obtain the knowledge from local pastoralists and experts if empirical knowledge is unavailable. When the method was applied to predict the crop yield, the results demonstrated an increase in crop yield predicability to an accuracy of 97% compared to 58% using traditional models for field peas and to 95% compared to 60% - 70% from models that depend on growing seasonal rainfall alone for wheat. The reason that this method can give better explanation of the variance in determining production could be: 1) the use of fuzzy membership functions enables variables with vague (imprecise) boundaries to be used; which is probably a better representation of the real world situation; and 2) the consideration of how variables interact to affect production.

The integrated method taken here gives a methodology for determining the relative importance of the soil and climate variables in determining rangeland production and crop yields. The relative importance of these variables can be used in assessing land capability for rangeland and crop production. The aggregated knowledge model also provides a mechanism for reasoning about data sets that always remain incomplete. In addition, when empirical data do not fit the membership function, the explanations obtained considering outriders provide a sound basis for knowledge acquisition. For example, when considering (Figure 3.6) wheat and peas (Figure 4.3) in the values from trial sites A, B, C and D indicate variance with the expected yield membership function constructed from climatic and soil variables. The reasons given for these outriders are presented in Table 3.4 for wheat and Table 4.4 for peas. From a knowledge acquisition view, outriders such as in A, B, C and D provide an interesting basis on which to focus discussion on exceptional or unusual cases. The explanations for the outliers define the boundaries of domain knowledge. Their explanation requires expert intervention and they can be used to elicit knowledge-base rules. For example, on examination of the data of rangeland production, it was found that outlier points marked A, B, C, D, E and F were coarse sands. This would be a constraint to plant roots obtaining water. To account for this, a constraint of 0.8 was applied in Relation 2. This increased the explanation of variance (R^2) from 0.74 to 0.81.

Another advantage of this method is that when no empirical knowledge is available, weightings in the interaction matrix could be obtained from local experts and land users. Land users and local experts are asked the importance of the variables considered. For example, they are asked what they consider from their experience are the least important, marginally important, important, very important and most important factors in determining production (see Introduction, Section 4.3). From their answers weightings can be derived. In wheat yield analysis, the results obtained using weighting's derived from expert knowledge are compared with those from a least square analysis. The results showed that expert knowledge can be satisfactorily used to estimate yields. This is considered important as it gives a means of estimating crop yields and rangeland production when data is limiting, as in developing countries.

Deriving weightings from local experts and land users could render this type of model to be easily adapted to different circumstances. Many models developed successfully under a given set of conditions are often expected to apply to other conditions, such as another crop, region, scale, process, or level. However, most of the models were designed for a specific location and they lack the ability to deal with the change in the importance of the variables for other locations. Hence, the remodels tend to be inflexible. This problem could be solved by refining or validating these specific models. However, this needs local data collection and testing. Many workers do not have the resources to do this. There is a need for flexible models that are easy to use and reliable. The weightings derived from the knowledge of local experts and land users can avoid detailed and expensive data collection to refine or validate a model.

Deriving weightings from local experts or land users might also lead to subjective results. This is considered dangerous. Some land users, because of their limitation of experience and education could give a weightings which might not fully represent the local situations. This could be overcome by interviewing many land users or experts. A weighting set given by one person can be confirmed or refined by others. Weighting sets could also be obtained from a statistical survey of many different land users or experts.

Further study should focus on the application of this method to different areas or regions. The relationship of the aggregated weighted index (A*) and rangeland production in Chapter 2 was obtained wide-world from data sets. The weighting sets in the model can only represent general universal situations. Relating to a particular area the assignment of weightings to variables might change. For example, slope which considers important to rangeland production in the Xinjiang region of China, might become less important in South Australia. Slopes in SA are much less steep. This makes the influence of run off water more important in Xinjiang. The ability to adjust weightings gives flexibility to these models.

The crop models developed in Chapters 3 and 4 were for wheat and peas was under South Australian conditions. For different crops in different areas the weighting adjustments could be different. With further use and experience weightings can be refined.

The method was further extended into two comprehensive evaluation models. One was used to comprehensively estimate the environmental impacts of agricultural land uses, and the other was used for comprehensive evaluation in determining the selection of a preferred crop for given conditions. This considered the biophysical, social-economic and environmental effects in the choice. The comprehensive evaluation models can integrate wide range of scientific multi disciplines and incorporate human knowledge and experience.

Developing models such as these is important for agriculture land evaluation, which intends to apply scientific disciplines to describe the land structure and function, and ultimately agricultural land use types. However, the land manager in most cases does not consider the scientifically determined values or recommendations. The reason for this is that the decisions usually do not involve the opinions of the land managers or users. The land manager has no confidence or even doubts that the decisions and recommendations made can be adapted to their particular situations.

The comprehensive evaluation model described gives a means of combining multi-disciplinary knowledge gained from experience, observation and experiment in a comprehensive and numeric way. Land managers can make decisions on the interaction of a wide range of considerations eg biophysical land capability , economic, management ability, environmental effects and personal preference and goals. Land managers can use the methods described to synthesise information to help reach their objectives. The advantages is that because they are personally involved in the decision making process, they have confidence in their conclusions and recommendations.

Testing of the models requires their application to a wide range of areas and conditions. Through this application, continuing improvement can be made possible.

The future of the world will depend on the sustainable use of its natural resource. As scientists, we have assembled a wide range of tools to tackle many aspects of natural resource problems. However, we do not, and never will know all that there is to be known, and we will forever make management decisions with inadequate information combined with a good deal of common sense (Smiles, 1992). The work described here addresses this need.

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