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GEODERMA

Geoderma 70 (1996) 1–19

Application of fuzzy logic to land suitability for rubber production in peninsular Thailand

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Received 22 April 1994; accepted 24 August 1995

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AN INTERNATIONAL JOURNAL OF SOIL SCIENCE

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Publication information
Geoderma (ISSN 0016-7061). For 1996 volumes 69–74 are scheduled for publication. Subscription prices are available upon request from the publisher. Subscriptions are accepted on a prepaid basis only and are entered on a calendar year basis. Issues are sent by surface mail except to the following countries where air delivery via SAL is ensured: Argentina, Australia, Brazil, Canada, Hong Kong, India, Israel, Japan, Malaysia, Mexico, New Zealand, Pakistan, PR China, Singapore, South Africa, South Korea, Taiwan, Thailand, USA. For all other countries airmail rates are available upon request. Claims for missing issues must be made within six months of our publication (mailing) date. Please address all your requests regarding orders and subscription queries to: Elsevier Science B.V., Journal Department, P.O. Box 211, 1000 AE Amsterdam, The Netherlands. Tel.: +31-20-4853642, fax: +31-20-4853598.

US mailing notice – *Geoderma* (ISSN 0016-7061) is published montly by Elsevier Science B.V. (Molenwerf 1, Postbus 211, 1000 AE Amsterdam). Annual subscription price in the USA US$ 1482 (US$ valid in North, Central and South America), including air speed delivery. Application to mail at second class postage rate is pending at Jamaica, NY 11431.
USA POSTMASTERS: Send address changes to *Geoderma*, Publications Expediting, Inc., 200 Meacham Avenue, Elmont, NY 11003.
Airfreight and mailing in the USA by Publications Expediting.

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Abstract

This paper aims to determine the quantitative impact of land qualities on rubber production, using the theory of fuzzy logic. This theory is applied in a land suitability assessment for rubber production in the northern part of the rubber growing area of peninsular Thailand. The proposed method differs from the usual technical land evaluation procedures by (1) the use of an explicit weight for the effect of each land quality on crop performance, and (2) the way of combining the evaluation of land qualities into a final land suitability class or land suitability index. The methodology was tested by comparing the estimated yields and land indices calculated by fuzzy set theory with those obtained by conventional procedures: (1) maximum limitation method; (2) parametric-Storie method, and (3) multiple linear regression. In the last approach the land index is replaced by the predicted relative yield from multiple regression on the various land qualities. The considered rubber clone, RRIM 600 is grown on a wide range of soils under different climatic conditions. The best relationship is given by the fuzzy set approach, which illustrates the potential usefulness of this theory in land evaluation.

1. Introduction

The development of a physical land suitability classification is a prime requisite for land use planning and development, because it guides decisions on land utilization towards an optimal utilization of land resources.

The accuracy of agricultural land evaluation depends on the significance of the chosen land qualities, with respect to their effects on crop production (Tang et al., 1991; Tang and Van Ranst, 1992). Several procedures for estimating the impact of land

0016-7061/96/$15.00
SSDI 0016-7061(95)00061-5

qualities on crop production were established by field scientists, on the basis of reasoned intuition. A well-known, simple approach is the "maximum limitation method" — Liebig's law of the minimum: plant growth is regulated by the most limiting factor (Sys, 1978, Sys, 1985; Zheng et al., 1989; Sys et al., 1991; Van Diepen et al., 1991). In these approaches, the most severe individual limiting land quality governs the overall suitability. Other procedures attribute a factor to each land quality that reduces the expected yield by a certain fraction. Examples of this approach are the "Storie index" (Storie, 1976), and "the Sys parametric approach" (Sys, 1978, Sys, 1985; Sys et al., 1991). Disadvantages of the above mentioned methodologies are: arbitrary selection of land qualities, poor definition of land productivity factors, experience-dependent decisions and spurious precision of results.

This paper employs another approach using fuzzy logic (Chang and Burrough, 1987) to determine the quantitative impact of land qualities on rubber production in peninsular Thailand.

2. Materials and methods

2.1. Materials

The study area (Fig. 1) is located in the northern part of the traditional rubber growing area of peninsular Thailand and covers a total area of 41,563 km^2. The geological formations are mainly sedimentary, locally metamorphosed and intensively folded, with some granites, granodiorites and diorites. The physiographic sub-regions of the study area include: hilly uplands and low mountains in the west, lowlands in the centre, and coastal lowlands in the east and west. The climate is of the tropical monsoon type. The natural vegetation is tropical rainforest. A total of 28 land units, defined according to topography, climate and soil, planted with the officially recommended (Sinthurahat, 1992) rubber clone, RRIM 600, of the same age were selected for this study. The units are spread over 5 reference areas (Fig. 1). The classification of the dominant soil of the different land units, and the average dry rubber yield for each land unit are given in Table 1.

According to Sinthurahat (1992), the following land qualities have an effect on rubber production in the study area: soil rooting conditions (effective rooting depth); availability of nutrients; oxygen availability; water availability, temperature regime, workability and erodibility. The values of these land qualities for each land unit are given in Table 2. Nutrient availability has been assessed with regard to the fertility status; determined by the NH_4OAc exchangeable basic cations (Ca, Mg, K), cation exchange capacity (CEC), organic carbon content (OC) and pH measured in water. Oxygen availability has been assessed according to drainage conditions. Water availability has been evaluated according to effective rainfall (expressed as a percentage of the rubber evapotranspiration during the tapping months) taking into account the storage capacity of the soil (Sinthurahat, 1992). Workability has been assessed according to texture, structure and consistency (moist) of the topsoil (0–15 cm). The temperature regime has been expressed in terms of altitude.

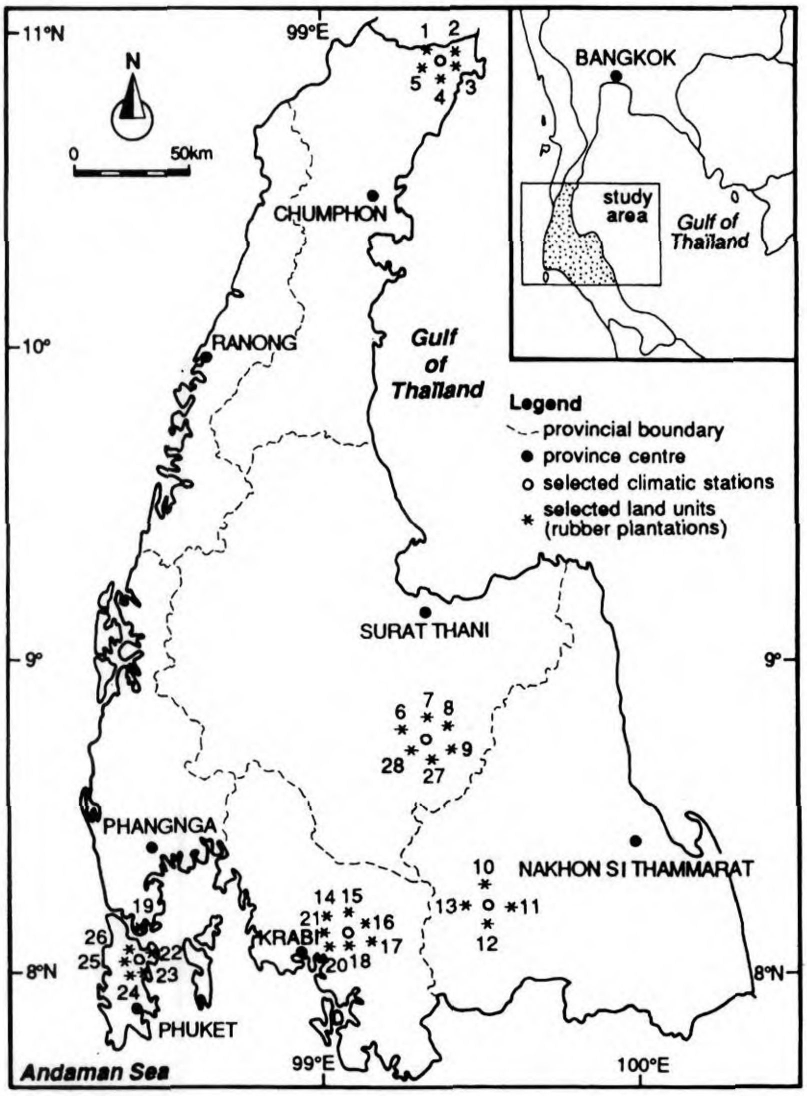

Fig. 1. Location of the study area with the selected land units.

2.2. Conventional land evaluation procedures

In the previous land evaluation procedures mentioned in this study, the land quality values are grouped into 4 classes (S1, S2, S3, N), according to the rubber requirements (Table 3). In addition, each class is assigned a numerical rating on a scale from 1 to 0. For example, if a land quality is considered optimal (no limitations) for rubber production, a value of 1 is attributed; if the same land quality has a limitation, a smaller value will be given.

Table 1
Classification of the dominant soils and average dry yield of each land unit

Land unit	Soil classification (Soil Survey Staff, 1992)	Average dry yield ($kg\ ha^{-1}\ yr^{-1}$)
1	Typic Kandiudox, very fine clayey, kaolinitic	1615
2	Typic Paleudults, fine-loamy, kaolinitic	853
3	Typic Kandiudults, fine-loamy, kaolinitic	1565
4	Typic Kandiudults, fine-loamy, mixed	864
5	Typic Quartzipsamments, sandy, siliceous	726
6	Typic Kandiudults, fine-loamy, mixed	1629
7	Typic Kandiudults, fine-loamy, kaolinitic	1603
8	Plinthic Kandihumults, clayey, kaolinitic	1221
9	Typic Kandiudox, very-fine clayey, kaolinitic	1760
10	Typic Palehumults, fine-clayey, mixed	1256
11	Plinthic Kandihumults, fine-clayey, kaolinitic	1634
12	Typic Palehumults, fine-clayey, mixed	2351
13	Lithic Dystropepts	933
14	Typic Kandiudults, coarse-loamy, kaolinitic	1224
15	Typic Kandiudults, fine-loamy, kaolinitic	1254
16	Typic Kandiudults, fine-clayey, kaolinitic	1715
17	Plinthohumults, fine-clayey, mixed	1252
18	Typic Kandihumults, very-fine clayey, kaolinitic	1861
19	Typic Kandihumults, fine-clayey, kaolinitic	2095
20	Typic Haplohumults, fine clayey, mixed	1170
21	Typic Kandihumults, fine clayey, kaolinitic	1382
22	Typic Kandihumults, fine clayey, kaolinitic	1967
23	Plinthic Kandihumults, fine clayey, kaolinitic	1256
24	Typic Kandihumults, fine clayey, kaolinitic	2052
25	Kandic Plinthohumults, fine clayey, kaolinitic	1625
26	Typic Kandiudults, fine clayey, kaolinitic	1505
27	Typic Kandiudults, fine-loamy, mixed	1028
28	Typic Quartzipsamments, sandy, siliceous	787

These conventional systems, however, differ in the way a final land index or score is calculated. The index is used to determine the land suitability class. The land suitability classes in this study use the ranges of land indices that are given in Table 4. In the maximum limitation method, the land suitability is defined according to the most severe limitation of land qualities and the land index is calculated by multiplying the lowest rating value by 100. The land index is eventually used to correlate with yield. In the parametric approaches, all individual land quality rating values are multiplied to produce one numerical index. According to the Storie method (Storie, 1976), the land index is the product of the individual rating values of all land qualities, using the following formula:

$$\mathrm{LI} = \left(\prod_{j=1}^{n} R_j \right) \cdot 100$$

where LI is the land index, n is the number of land qualities and R_j is the rating value of the jth quality. In the multiple linear regression approach the land index is replaced

Table 2
Land qualities of representative land units in peninsular Thailand

Land unit	Effective rooting depth (cm)	Availability of nutrients (0–25 cm)						Oxygen availability (drainage class)	Water availability (%)	Temperature regime (altitude, m)	Workability	Erodibility (slope, %)
		Ca [a]	Mg [a]	K [a]	CEC [a]	O.C (%)	pH (H_2O)					
1	200	0.3	0.5	0.1	10.2	2.6	5.3	well	66	40	easy	1
2	200	1.5	0.6	0.2	6.8	2.6	5.0	well	66	80	moderate	16
3	200	2.2	0.7	0.1	6.9	2.2	5.5	well	66	60	easy	4
4	200	2.5	0.5	0.2	6.4	2.6	5.5	well	66	100	moderate	20
5	200	0.5	0.4	0.1	4.7	1.1	5.0	well	66	20	easy	1
6	200	2.6	0.7	0.1	7.2	2.6	5.1	well	75	20	easy	4
7	200	1.0	0.5	0.1	7.0	2.1	5.0	well	75	40	easy	4
8	200	1.2	0.6	0.1	4.8	1.7	5.5	well	75	40	easy	7
9	200	2.0	0.3	0.1	10.5	2.4	5.3	well	74	20	easy	4
10	200	1.0	0.4	0.1	12.1	2.7	5.0	mod. well	81	10	easy	1
11	200	0.3	0.4	0.2	10.4	2.2	4.9	well	80	60	moderate	17
12	200	2.4	0.5	0.1	10.4	2.0	5.0	well	81	50	easy	1
13	50	2.7	0.7	0.3	16.7	2.0	4.8	well	74	60	moderate	18
14	200	0.9	0.4	0.1	6.4	1.1	5.5	well	77	20	easy	4
15	200	0.8	0.3	0.1	7.7	2.0	5.0	mod. well	71	10	easy	4
16	200	1.1	0.4	0.1	8.5	1.8	5.0	well	77	40	easy	1
17	200	1.8	0.8	0.1	8.9	2.3	5.5	well	77	30	easy	1
18	200	2.9	0.5	0.1	6.8	2.7	5.5	well	77	50	easy	2
19	200	2.9	0.4	0.3	10.6	2.2	5.1	well	81	40	easy	7
20	200	0.6	0.4	0.1	7.7	1.4	5.0	well	77	40	moderate	12
21	200	1.3	0.8	0.4	7.9	2.1	5.0	well	77	40	moderate	10
22	200	0.4	0.4	0.2	10.6	2.8	4.5	well	77	25	easy	4
23	200	0.4	0.5	0.2	7.5	1.0	4.5	mod. well	81	20	easy	4
24	200	2.9	0.4	0.2	10.7	2.6	5.0	well	79	40	moderate	15
25	200	0.6	0.3	0.2	6.7	2.8	5.0	well	81	30	moderate	10
26	200	2.8	0.7	0.3	8.9	2.1	5.0	well	81	50	moderate	30
27	200	1.3	0.4	0.1	7.7	2.5	5.0	well	75	30	moderate	22
28	200	0.3	0.2	0.1	4.9	1.1	5.1	well	75	20	easy	1

[a] Values in cmol(+)/kg soil.

by the predicted relative yield from multiple regression on the various land qualities, calculated using the following formula:

$$Y = C + \sum_{j=1}^{n} w_j X_j$$

where Y is the predicted relative yield from multiple regression, n is the number of land qualities and X_j is the value of the jth land quality. The coefficients C and w_j are obtained by minimizing the so-called sum of squares. However, it is possible to use the rating values for the different land qualities we choose to use original data, because they will reveal more the variation within the data sets.

2.3. *Fuzzy set approach*

The fuzzy set theory, originally proposed by Zadeh (1965), was developed to deal with vaguely defined expressions, classes or categories, e.g. "important" and "less

Table 3
Land suitability requirements for rubber based on land qualities

Land qualities	Suitability class and rating scale			
	S1 1.0	S2 0.85	S3 0.60	N 0.40
Effective rooting depth (cm)	> 150	150–100	100–50	< 50
Available nutrients (0–25 cm)				
Ca (cmol(+)kg^{-1} soil)	< 3.5	3.5–4.5	> 4.5	–
Mg (cmol (+) kg^{-1} soil)	< 0.7	0.7–0.9	> 0.9	–
K (cmol (+) kg^{-1} soil)	> 0.2	< 0.2	–	–
CEC (cmol (+) kg^{-1} soil)	> 6.0	< 6.0	–	–
OC (%)	> 1.0	< 1.0	–	–
pH	4.0–6.0	6.0–6.5	> 6.5	–
			< 4.0	–
Oxygen availability (drainage class)	well to moderately well	moderately well to somewhat poorly	poorly	very poorly
Water availability (%)	80	80–60	60–40	< 40
Temperature regime (altitude, m)	< 250	250–400	400–500	> 500
Workability	easy	moderate	difficult	very difficult
Erodibility (slope %)	< 20	20–40	40–60	> 60

important''. Although each of these expressions conveys a useful meaning, obvious for a certain community, quantification of the degree of importance of land qualities on crop performance usually is a difficult task. To deal with such cases, the concept of fuzzy sets is used. In the classical set theory, an element either belongs to a set A or not:

$$(\forall x \in A)\ (x \in A \text{ or } x \notin A)$$

The corresponding membership function only takes two values: 0 ($x \notin A$) and 1 ($x \in A$). In contrast a fuzzy set A is a mapping from A to the unit interval [0, 1]:

$$(\forall x \in A)\ (A(x) \in [0, 1])$$

The value $A(x)$ is called the ''degree of membership'' of x in A. Fig. 2 illustrates graphically the difference between the traditional (or crisp) and fuzzy sets.

The concept of ''degree of belonging'' can be represented in a characteristic function called the ''membership function''. In this way, the degree of belonging of a land

Table 4
Land index limits used by different methods for classifying land suitability classes

Land index	Land suitability class
75–100	S1: very suitable land
50–75	S2: moderately suitable land
25–50	S3: marginally suitable land
0–25	N: unsuitable land

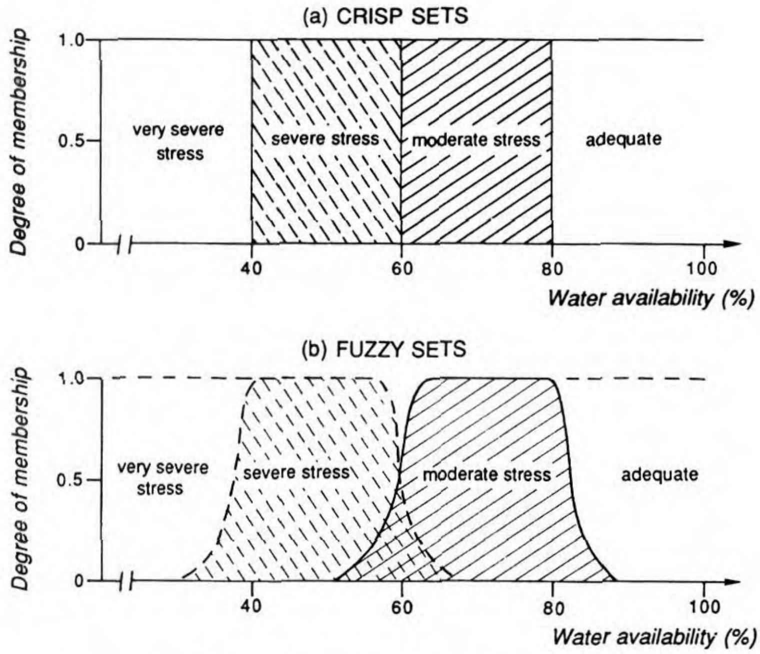

Fig. 2. Graphical presentation of crisp and fuzzy sets.

quality can be expressed by values between 0 and 1; 1 for the most important land quality and 0 for the least important one.

For each land quality and each observed yield, membership functions have to be established for all suitability classes, defined by FAO (1976), based on rubber requirements (Table 3). Membership functions express the degree to which the value of a land quality, or of an observed yield, belongs to a certain suitability class. There are three basic forms of membership functions used: triangular, bell-shaped and trapezoidal. For each of the three forms, symmetrical or asymmetrical functions may be chosen with

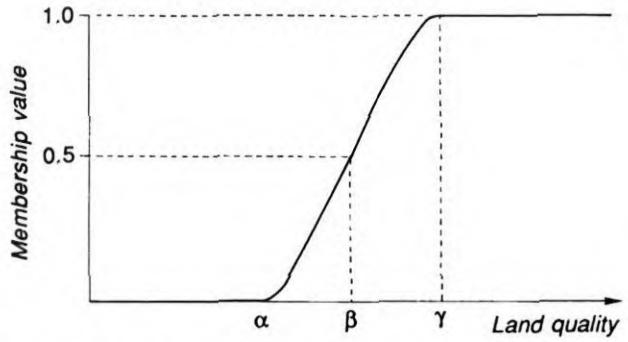

Fig. 3. Graphical presentation of the S-membership function (Tang et al., 1991).

regard to the central concept and degree of dispersion of the boundaries for a considered land quality (Burrough, 1989). In this study, the S-membership function (similar to the bell-shaped) has been used, because it gives the best results among the different shapes of membership functions.

If a value of a land quality, or of an observed yield, belongs completely to the considered class, its membership value is 1. If this value absolutely does not belong to the considered class, its membership value is 0. If this value belongs to some extent to the considered class, an intermediate membership value will be computed by the S-membership function (Tang et al., 1991). The S-membership function is defined as:

$$S(x;\alpha,\beta,\gamma)=\begin{cases}0; & x \in \,]-\infty,\alpha[\\ 2[(x-\alpha)/(\gamma-\alpha)]^2; & x \in [\alpha,\beta[\\ 1-2[(x-\gamma)/(\gamma-\alpha)]^2; & x \in [\beta,\gamma[\\ 1; & x \in [\gamma,+\infty[\end{cases}$$

where $\beta=(\alpha+\gamma)/2$ (see Fig. 3). This function will be used to describe the increase of belonging to a suitability class; its complement represents the decreasing membership $1-S$.

Evaluation of land qualities and classification of observed yield per land unit, requires the determination of the degree of membership of each assessed land quality and observed yield to the different suitability classes. The results of the allocation of all land qualities per land unit to suitability classes are set out in a characteristic matrix (R). The results of classification for an observed yield are set out in a standard suitability matrix (P) of membership values for all the considered suitability classes.

Different land qualities have different impacts on rubber cultivation. Their relative effect with regard to rubber yield can be expressed by a weight factor. The weight values for all land qualities will form a weight matrix (W), which expresses the effect of the land qualities on rubber yield. The final suitability classification (evaluation matrix E), using fuzzy logic, is obtained by multiplying the characteristic matrix (R) with the weight matrix (W), i.e. $E=W\circ R$.

3. Results and discussion

3.1. Quantitative impact of land qualities on rubber production

The application of the fuzzy set theory to determine the impact of land qualities on rubber production comprises several steps:

3.1.1. Determination of membership functions

For each land quality the critical values $(\alpha,\ \beta,\ \gamma)$ of membership functions are usually difficult to be determined by statistical analysis and are therefore selected, based on expert judgement and experience, for the different suitability classes, as shown in

Fig. 3. For the land quality "water availability", the following membership functions for suitability class S1 are used:

$$S1 = S(x;60,70,80) = \begin{cases} 0; & x \in [0,60[\\ 2[(x-60)/20]^2; & x \in [60,70[\\ 1-2[(x-80)/20]^2; & x \in [70,80[\\ 1; & x \in [80,100] \end{cases}$$

where x is water availability in % and $x \in [0,60[$ signifies that x can be any value between 0 and 60. Membership functions for the other suitability classes (S2, S3 and N) are based on the same principles as for S1. Similar S-membership functions are established for the other land qualities that are considered in the study.

The membership functions for observed yields (Table 1) are also obtained by using the S-membership function:

$$S1 = S(y;1200,1500,1800)$$

$$S2 = \begin{cases} S(y;600,900,1200) \\ S(y;1200,1500,1800) \\ 1 - S(y;1800,(1800+v)/2,v) \end{cases}$$

$$S3 = \begin{cases} S(y;0,300,600) \\ S(y;600,900,1200) \\ 1 - S(y;1200,1500,1800) \end{cases}$$

$$N = 1 - S(y;600,900,1200)$$

where y is the observed dry yield in kg ha^{-1} yr^{-1} and v is the maximum value of the observed yields. The membership functions for the respective suitability classes are presented graphically in Fig. 4.

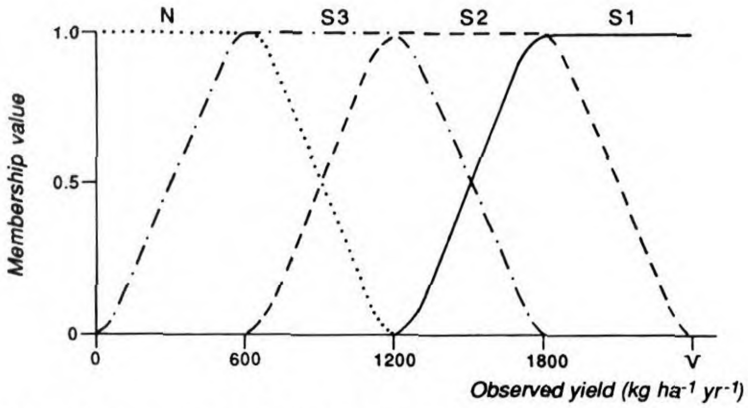

Fig. 4. Graphical presentation of membership functions (S1, S2, S3 and N) for observed yield.

3.1.2. Determination of membership values

For each land unit, the membership values of the different land qualities and suitability classes are computed using the pre-determined membership functions for numerical land qualities and the crisp set concept for non-numerical land qualities, e.g. oxygen availability and workability. The membership values are subsequently arranged in a characteristic matrix (R). An example, using the data of land unit 1, is given below:

$$R = \begin{array}{c} \\ \text{RD} \\ \text{CA} \\ \text{MG} \\ \text{K} \\ \text{EC} \\ \text{OC} \\ \text{PH} \\ \text{AO} \\ \text{AW} \\ \text{TR} \\ \text{WB} \\ \text{ER} \end{array} \begin{array}{c} \begin{array}{cccc} \text{S1} & \text{S2} & \text{S3} & \text{N} \end{array} \\ \begin{bmatrix} 1 & 0.78 & 0.50 & 0.06 \\ 1 & 0.02 & 0.01 & 0 \\ 1 & 0.79 & 0.24 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0.18 & 1 & 0.32 & 0 \\ 1 & 0.05 & 0.02 & 0.01 \\ 1 & 0 & 0 & 0 \\ 1 & 0.01 & 0 & 0 \end{bmatrix} \end{array}$$

where RD is effective rooting depth; CA is exchangeable calcium, MG is exchangeable magnesium, K is exchangeable potassium, EC is the cation exchange capacity, OC is organic carbon, PH is the pH in water, AO is oxygen availability, AW is water availability, TR is temperature regime, WB is workability and ER is erodibility.

The element r_{ij} of matrix R denotes the membership value for the ith land quality under the jth suitability class ($i = 1, 2, 3, ..., 12$; $j =$ S1, S2, S3 and N). For example the element $r_{9,1} = 0.18$ indicates that for a water availability of 66% (land unit 1), the membership value of water availability within class S1 (based on the formula of the membership functions for S1) is equal to 0.18.

Membership values for observed yields are also calculated using the pre-determined membership functions. The membership values are subsequently arranged in a standard suitability matrix (P). For land unit 1, the following matrix (P) is obtained:

$$P = \begin{array}{c} \begin{array}{cccc} \text{S1} & \text{S2} & \text{S3} & \text{N} \end{array} \\ [0.81 \quad 1.0 \quad 0.19 \quad 0] \end{array}$$

The element p_j of matrix P denotes the membership value for land unit 1 under jth suitability class ($j =$ S1, S2, S3 and N). For example, the element $p_1 = 0.81$ indicates that for an observed yield of 1615 kg ha^{-1} yr^{-1} (land unit 1), the membership value of the observed yield within class S1 (based on the formula of the membership functions for S1 [$S1 = S(y; 1200, 1500, 1800)$)] is equal to 0.81.

3.1.3. Determination of reference weight and reference suitability matrices

A weight value ranges between 1 and 0. The highest value (i.e. 1) indicates the most important land quality, a lower value indicates a less important one. Reference suitabil-

Table 5
Most important examples of triangular norm T and triangular conorm T^* (Ruan, 1990)

Triangular norm T	Triangular conorm T^*
Minimum	**Maximum**
$S(m_t, r) = \min(m_t, r)$	$S^*(m_t, r) = \max(m_t, r)$
continuous, positive, non-Archimedean	
Product	**Probabilistic sum**
$\Pi(m_t, r) = m_t \cdot r$	$\Pi^*(m_t, r) = m_t + r - m_t \cdot r$
continuous, positive, Archimedean	
Bounded product	**Bounded sum**
$S(m_t, r) = \max(0, m_t + r - 1)$	$S^*(m_t, r) = \min(m_t + r, 1)$
continuous, nonpositive, Archimedean	
Drastic product	**Drastic sum**
$S(m_t, r) = \begin{cases} \min(m_t, r); & \max(m_t, r) = 1 \\ 0; & \text{elsewhere} \end{cases}$	$S^*(m_t, r) = \begin{cases} \max(m_t, r); & \min(m_t, r) = 1 \\ 1; & \text{elsewhere} \end{cases}$
noncontinuous, nonpositive, Archimedean	

m_t represents weight matrix (M).
r denotes the characteristic matrix (R).

ity matrices are established by attributing randomly selected values between 1 and 0 (100,000 in this study) to each of the considered land qualities. A combination of 12 randomly selected values, one attributed to each land quality, is used to construct a reference weight matrix. Because 100,000 selections are carried out, the same number of reference weight matrices (M_t, $t \in \{1; 2; ...; 100,000\}$) are constructed. For example the reference weight matrix at the 500th ($t = 500$) selection is:

M_{500}	=[RD	CA	MG	K	EC	OC	PH	AO	AW	TR	WB	ER]
	=[0.12	0.35	0.57	0.24	0.33	0.21	0.18	0.47	0.69	0.16	0.43	0.27]

Reference suitability matrices (S_t, $t \in \{1; 2; ...; 100,000\}$) are obtained by combining the reference weight matrices (M_t) with the characteristic matrix (R) (Tang and Van Ranst, 1992) using a fuzzy set operator:

$$S_t = M_t \circ R$$

where " $\circ$ " is the fuzzy set operator which has been generated from a triangular norm T and a triangular conorm T^* (Ruan, 1990; Kerre, 1991). There are many examples of triangular norms T and triangular conorms T^* and the most important ones are given in Table 5. However, based on calculations using these norms, the best results for reference suitability matrices (S_{tj}) were obtained by the following formula (bounded product, bounded sum):

$$s_{tj} = \min(a_1 + a_2 + \cdots + a_n, 1)$$

$$\text{with } a_i = \max\left(0, m_{ti} + r_{ij} - 1\right),\ i = 1, ..., n$$

where $t \in \{1; 2; ...; 100,000\}$, j represents S_1, S_2, S_3 and N, a_1, a_2, ... and a_n denote the results of $\max(0, m_{ti} + r_{ij} - 1)$ for the ith land quality; m_{ti} represents the reference weight value for the ith land quality, and r_{ij} denotes an element of matrix R, i.e. for the ith land quality under jth suitability class.

The operator performs the same operation as the multiplication of two matrices in algebra. However, the multiplication of two matrix elements is replaced by the determination of the maximum value of $\max(0, m_{ti} + r_{ij} - 1)$ of the two matrix elements; the addition of products of elements is replaced by the determination of the minimum value of $\min(a_1 + a_2 + \cdots + a_i, 1)$ for all products. The calculation procedure is illustrated by a simple example, considering only two land qualities:

$$s_{tj} = min(a_1 + a_2, 1)$$

$$\text{with } a_i = \max(0, m_{ti} + r_{ij} - 1), \quad i = 1,2$$

S is the result of combining the reference weight matrix (M) and characteristic matrix (R):

$$S = [0.3\ 0.9] \circ \begin{matrix} & \text{S1} & \text{S2} & \text{S3} & \text{N} \\ \text{RD} & 1 & 0.61 & 0.30 & 0.10 \\ \text{CA} & 1 & 0.86 & 0.47 & 0 \end{matrix}$$

$$\begin{matrix} & \text{S1} & \text{S2} & \text{S3} & \text{N} \\ = [& 1 & 0.76 & 0.37 & 0] \end{matrix}$$

It follows that:

$$\begin{aligned} S_1 &= \min\{[\max(0,0.3+1-1)+\max(0,0.9+1-1)],1\} \\ &= \min[0.3+0.9,1] \\ &= 1 \end{aligned}$$

The values of S2, S3 and N are calculated in the same way.

3.1.4. Determination of weight values for different land qualities

The more a reference suitability matrix (S_t) approaches the standard suitability matrix (P), the better is the associated weight matrix (M_t). The weight matrix (M_t) that brings S_t the closest to P (best calibration) will be retained. Therefore, based on the relationship between the standard suitability matrix (P) and the reference suitability matrix (S_t), a fuzzy set G (based on the set of all reference weight matrices M_t) can be established, considering the following membership function V_G (Tang and Van Ranst, 1992; Tang, 1993):

$$V_G(M_t) = 1 - d(S_t, P)$$

where d is a normalized distance between the reference suitability matrix (S_t) and standard suitability matrix (P):

$$d(S_t, P) = \sqrt{\left(\sum_{j=1}^{4} (s_{tj} - p_j)^2\right)/4}$$

$V_G(M_t)$ is the degree to which S_t approaches P, or the degree to which M_t is suited to be used as weight values.

It is obvious from the membership function $V_G(M_t)$ that the smaller the distance between S_t and P, the higher the value for $V_G(M_t)$. Hence, we selected the weight matrix that corresponds to the highest membership value of $V_G(M_t)$ as the best weight value for the different land qualities. For instance, the best weight values of different land qualities for land unit 1 are calculated and presented as follows:

$$\begin{array}{lllllllllllllll} M_{46898} & =[& \text{RD} & \text{CA} & \text{MG} & \text{K} & \text{EC} & \text{OC} & \text{PH} & \text{AO} & \text{AW} & \text{TR} & \text{WB} & \text{ER} &] \\ & =[& 0.03 & 0.16 & 0.19 & 0.21 & 0.13 & 0.15 & 0.09 & 0.04 & 0.76 & 0.02 & 0.31 & 0.26 &] \end{array}$$

0.26]

where M_{46898} signifies that at the 46,898th selection, the reference weight matrix (M_t, $t = 46{,}898$) corresponds to the highest membership value of $V_G(M_t)$.

The matrix indicates that for land unit 1, water availability (AW = 0.76) is the most important land quality and temperature regime (TR = 0.02) the least important land quality for rubber production.

The average values of the reference weight matrices, corresponding to the highest membership values of $V_G(M_t)$ for all land units studied, are subsequently considered as the weight values for the land qualities and are presented as a weight matrix (W):

$$W_a = \sum_{i=1}^{n} (M_i^a)/n$$

where W_a is the mean weight value for the ath land quality; $a \in$ {RD, CA, MG, K, EC, OC, PH, AO, AW, TR, WB, ER}, n is the number of land units, and M_i^a is the optimal

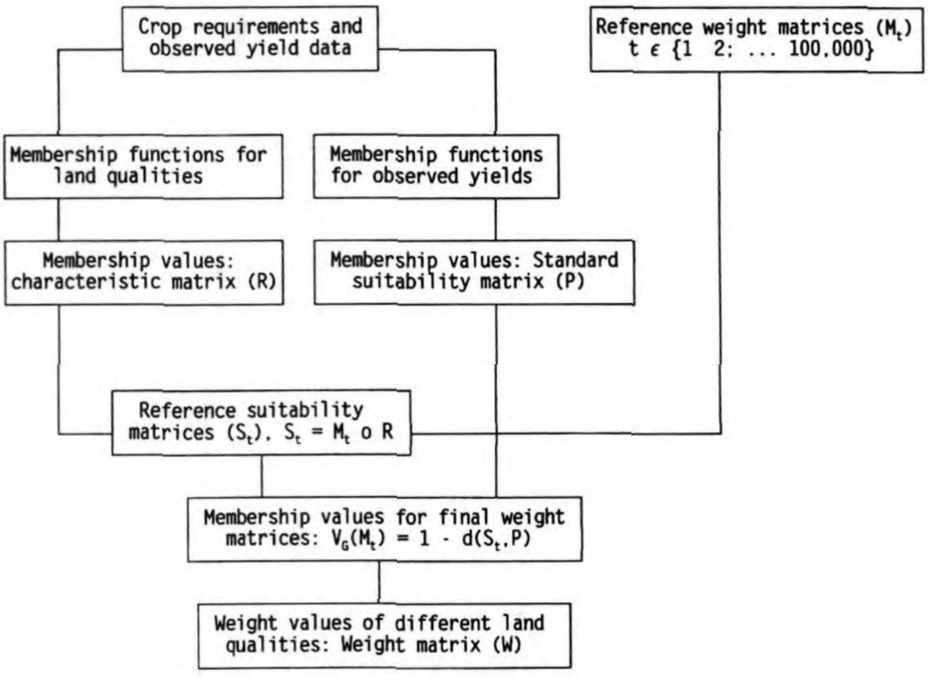

Fig. 5. Diagrammatic representation of the procedure.

Table 6
Weight values for different land qualities influencing rubber production in peninsular Thailand

Land unit	Weight values for different land qualities *											
	RD	CA	MG	K	EC	OC	PH	AO	AW	TR	WB	ER
1	0.03	0.16	0.19	0.21	0.13	0.15	0.09	0.04	0.76	0.02	0.31	0.26
2	0.07	0.11	0.11	0.11	0.18	0.19	0.16	0.12	0.64	0.05	0.34	0.16
3	0.11	0.12	0.11	0.14	0.14	0.15	0.09	0.16	0.69	0.14	0.25	0.15
4	0.08	0.09	0.21	0.19	0.12	0.11	0.11	0.09	0.66	0.16	0.14	0.08
5	0.08	0.14	0.11	0.16	0.32	0.13	0.06	0.04	0.62	0.08	0.49	0.19
6	0.03	0.11	0.13	0.24	0.11	0.16	0.06	0.08	0.76	0.11	0.24	0.22
7	0.02	0.12	0.18	0.16	0.18	0.11	0.14	0.02	0.74	0.06	0.45	0.21
8	0.04	0.13	0.14	0.18	0.29	0.16	0.06	0.04	0.73	0.11	0.28	0.12
9	0.05	0.12	0.12	0.19	0.17	0.18	0.04	0.11	0.78	0.06	0.37	0.24
10	0.12	0.13	0.16	0.21	0.18	0.21	0.16	0.06	0.64	0.08	0.28	0.21
11	0.11	0.13	0.11	0.15	0.24	0.21	0.07	0.16	0.82	0.09	0.31	0.28
12	0.05	0.14	0.22	0.16	0.21	0.15	0.09	0.05	0.86	0.17	0.23	0.14
13	0.33	0.12	0.13	0.16	0.19	0.26	0.12	0.04	0.62	0.13	0.34	0.24
14	0.15	0.12	0.12	0.19	0.18	0.12	0.14	0.06	0.84	0.09	0.29	0.18
15	0.05	0.09	0.11	0.14	0.22	0.13	0.06	0.02	0.82	0.11	0.25	0.26
16	0.04	0.11	0.11	0.32	0.15	0.14	0.11	0.18	0.76	0.09	0.38	0.18
17	0.06	0.26	0.22	0.14	0.16	0.16	0.09	0.08	0.68	0.09	0.14	0.32
18	0.09	0.13	0.24	0.31	0.18	0.14	0.11	0.08	0.74	0.07	0.23	0.36
19	0.16	0.14	0.18	0.26	0.15	0.17	0.13	0.06	0.76	0.15	0.26	0.21
20	0.12	0.12	0.13	0.18	0.14	0.14	0.12	0.09	0.62	0.16	0.26	0.24
21	0.18	0.19	0.28	0.62	0.15	0.15	0.11	0.06	0.71	0.09	0.23	0.19
22	0.06	0.11	0.26	0.18	0.23	0.09	0.14	0.11	0.56	0.13	0.14	0.23
23	0.12	0.12	0.21	0.15	0.15	0.14	0.06	0.21	0.63	0.08	0.54	0.21
24	0.05	0.14	0.27	0.16	0.18	0.11	0.14	0.05	0.61	0.17	0.24	0.11
25	0.04	0.16	0.15	0.16	0.15	0.28	0.14	0.07	0.65	0.08	0.15	0.24
26	0.09	0.26	0.21	0.28	0.16	0.12	0.06	0.08	0.68	0.12	0.31	0.25
27	0.11	0.13	0.26	0.21	0.18	0.22	0.12	0.04	0.54	0.18	0.18	0.21
28	0.02	0.14	0.16	0.18	0.31	0.19	0.11	0.16	0.67	0.06	0.24	0.16
Mean	0.09	0.14	0.17	0.21	0.18	0.16	0.10	0.08	0.70	0.10	0.28	0.21

* RD: effective rooting depth; Available nutrients [CA: Ca; MG; Mg; K: K; EC: CEC; OC: organic carbon content] ; PH: pH(H_2O); AO: oxygen availability; AW: water availability; TR: temperature regime; WB: workability; ER: erodibility.

weight value of the *a*th land quality in the *i*th land unit (obtained from calibration procedure).

For example, the final weight value for water availability in the study area represented by 28 land units, is calculated as follows:

$$W_{AW} = [(0.76 + 0.64 + 0.69 + 0.66 + 0.62 + 0.76 + 0.74 + 0.73 + 0.78 + 0.64 + 0.82 + 0.86 + 0.62 + 0.84 + 0.82 + 0.76 + 0.68 + 0.74 + 0.76 + 0.62 + 0.71 + 0.56 + 0.63 + 0.61 + 0.65 + 0.68 + 0.54 + 0.67)]/28 = 0.70$$

The application procedure is presented graphically in Fig. 5.

The impact of the land qualities, which influence the performance of rubber yield in

28 representative land units of peninsular Thailand, has been evaluated by application of the fuzzy set method. Weight values of the land qualities are given in Table 6.

3.2. Physical suitability classification of rubber production

The results of the physical suitability classification of rubber production for the 28 representative soil units obtained by the maximum limitation method, parametric-Storie method and multiple linear regression are given in Table 7.

The final suitability classification using fuzzy logic is obtained by multiplying the two fuzzy matrices (W and R) established previously:

$$E = W \circ R$$

Table 7
Observed rubber yields, land suitability classes and land indices or predicted relative yield obtained by different methods for the different land units in peninsular Thailand

Land unit	Average dry yield (kg/ha/yr)	Land suitability evaluation for rubber by different methods			
		Maximum limitation method class (index)	Parametric Storie approach class (index)	Multiple linear regression (kg/ha/yr)	Fuzzy approach class (index)
1	1615	S2 (70)	S2 (56)	1405	S1/S2 (75)
2	853	S2 (70)	S3 (48)	880	S3 (32)
3	1565	S2 (70)	S2 (56)	1342	S2 (59)
4	864	S2 (70)	S3 (41)	1188	S3 (39)
5	726	S2 (70)	S3 (37)	906	S3 (33)
6	1629	S1 (80)	S2 (54)	1692	S2 (68)
7	1603	S1 (80)	S2 (62)	1506	S2 (60)
8	1221	S1 (80)	S3 (41)	1059	S3 (45)
9	1760	S1 (80)	S2 (64)	1730	S1 (77)
10	1256	S1 (80)	S3 (43)	1638	S2 (51)
11	1634	S1 (80)	S2 (52)	1549	S2 (65)
12	2351	S1 (80)	S1 (78)	2205	S1 (82)
13	933	S2/S3 (50)	S3 (27)	933	S3 (39)
14	1224	S1 (80)	S3 (44)	1072	S2 (56)
15	1254	S1 (80)	S3 (39)	917	S2 (53)
16	1719	S1 (80)	S2 (54)	1737	S1 (76)
17	1252	S1/S2 (75)	S3 (43)	1584	S2 (62)
18	1861	S1 (80)	S2 (59)	1816	S1 (81)
19	2095	S1 (90)	S1 (81)	2153	S1 (78)
20	1170	S1 (80)	S3 (41)	1175	S3 (48)
21	1382	S1/S2 (75)	S3 (38)	1380	S2 (57)
22	1907	S1 (80)	S2 (63)	1991	S1 (76)
23	1256	S1 (90)	S3 (39)	1211	S2 (62)
24	2052	S1 (80)	S2 (67)	1881	S1 (77)
25	1625	S1 (85)	S2 (54)	1430	S2 (59)
26	1505	S1/S2 (75)	S3 (47)	1474	S2 (61)
27	1028	S1 (80)	S3 (34)	1155	S3 (42)
28	787	S1 (80)	N (22)	1115	S3 (32)

The operator "∘" is the same as in the determination of the reference suitability matrix (S_t). Each element of the evaluation matrix is calculated using the formula:

$$E_j = \min(a_1 + \cdots + a_n, 1) \text{ with } a_i = \max(0, w_i + r_{ij} - 1)$$

The elements of the evaluation matrix (E) express the degree of membership of the considered land unit to the suitability classes from S1 to N. The suitability class for the land unit corresponds to the element of the matrix (E) with the highest value.

For example, in the evaluation of land unit 1 (Table 2), the evaluation matrix (E), defined as $E = W \circ R$, is equal to:

$$E = [0.03\,0.16\,0.19\,0.21\,0.13\,0.15\,0.09\,0.04\,0.76\,0.02\,0.31\,0.26] \circ \begin{bmatrix} 1 & 0.78 & 0.50 & 0.06 \\ 1 & 0.02 & 0.01 & 0 \\ 1 & 0.79 & 0.24 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0.18 & 1 & 0.32 & 0 \\ 1 & 0.05 & 0.02 & 0.01 \\ 1 & 0 & 0 & 0 \\ 1 & 0.01 & 0 & 0 \end{bmatrix}$$

$$\begin{matrix} & \text{S1} & \text{S2} & \text{S3} & \text{N} \\ = [& 1.00 & 0.97 & 0.08 & 0 \;] \end{matrix}$$

Because the matrix element with the highest value (1.0) indicates a degree of belonging to class S1, the land unit mainly belongs to suitability class S1 (very suitable).

In order to calculate a land index, the sum of the evaluation matrix (E) elements has to be set equal to 1 (standardization) and the new values are multiplied by the average indices of the different suitability classes (Table 4), respectively. The sum of the individual products will give the weighted land index.

$$\text{LI} = \Sigma\left[d(E_j) * A_j\right]$$

where LI is the land index, d is the normalized values of matrix E, and A is the average of the minimum and maximum index of the suitability classes, as defined in Table 4. Finally, land suitability classes are obtained from the weighted land indices using the same index limits given in Table 4.

The results of the suitability classification obtained using fuzzy logic (Table 7) were compared with (1) the results obtained by the other approaches (Table 7), and (2) the observed rubber yields on different land units (Table 1). The correlations between the land indices (predicted relative yields in case of the multiple regression approach) obtained by the different methods and the observed yields are shown in Fig. 6. The correlation coefficients are high for the multiple linear regression, the parametric and the fuzzy set approach. However, the results obtained with the latter method are in better

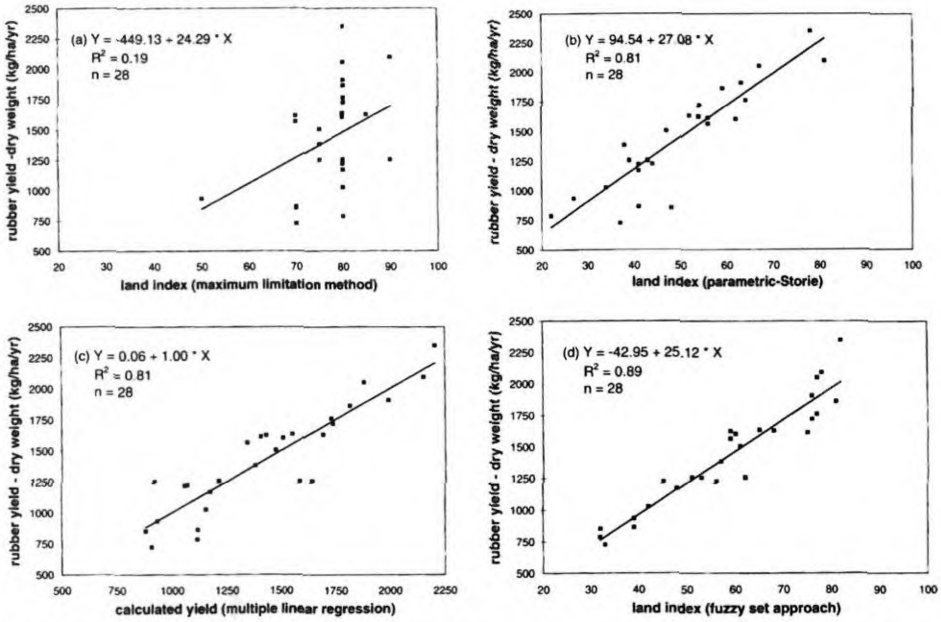

Fig. 6. Linear regression between land suitability indices or predicted relative yield obtained with (a) maximum limitation method, (b) parametric-Storie method, (c) multiple linear regression and (d) fuzzy logic, and observed rubber yield data in peninsular Thailand.

agreement ($R^2 = 0.89$) with the observed yields as compared to those obtained with the other three methods: maximum limitation ($R^2 = 0.19$); parametric-Storie method ($R^2 = 0.81$); multiple linear regression ($R^2 = 0.81$).

The results are in agreement with a study carried out by Sinthurahat (1992) in the same area. He concluded that water availability, workability, resistance against erosion and nutrient availability have an important impact on rubber cultivation. Weight values for different land qualities calculated by the fuzzy set approach correspond quite well with the matching results of land qualities (Table 2) and crop requirements (Table 3).

4. Conclusions

The fuzzy set approach differs from the conventional land evaluation procedures in its use of a calculated weight for the impact of each land quality on crop performance and in its way of combining the evaluation of the considered land qualities into a final suitability class or suitability index. In addition to a dominant suitability class, the fuzzy set methodology equally provides additional information on the "position" of a land unit within the suitability class relative to the neighbouring suitability classes. For example, the suitability classification result of land unit 1 indicates that, although land unit 1 has been classified as S1, it could also be classified, to a large extent, as S2, since the membership values of S1 (1.0) and of S2 (0.97) differ slightly. This information is useful for rational decisions on management practices. Fuzzy approach allows matching of individuals to be determined on a continuous scale instead of on an integer scale.

The strength of the fuzzy set approach is that it offers a way to create classes for the soil continuum in a continuous way. Another advantage is its premise that nature may be inherently vague or imprecise, and does not try to pretend that the real world, which has been modelled by data entities created by human observations, is more exact, or more perfect than it really is (Burrough et al., 1992).

However, the accuracy of each evaluation depends on the quality of weighing of land qualities, with respect to their effects on rubber production. A weakness in the proposed fuzzy logic approach is the way in which the weight values are determined, i.e., a new random selection of a large number of weight values will yield different final weight values for the different land qualities. Further research is needed to improve this part of the approach. Improvement can probably be obtained by the use of:

1. least squares method, because the formula $S_t = M_t \circ R$ can be considered as a system of equations with unknown coefficients; or
2. fuzzy relational calculus, where the formula $S_t = M_t \circ R$ is considered as a so-called round composition of fuzzy relations (De Baets and Kerre, 1994).

Land evaluation focusses increasingly on the application of quantitative procedures. Changes in procedures also call for the use of other kinds of data than hitherto collected. With respect to soil data, the common procedures of averaging and categorizing observed data are not ideal and no longer essential for recording and retrieving data now that computers are available. Numerical models need numerical data.

Despite the statistical procedures, the use of the fuzzy set theory to define, describe and generate the required numerical parameters from readily available soil survey data can play an important role. The results obtained with the fuzzy set method are very promising for its further development on how membership functions, class intervals and other parameters can be determined from the data themselves to yield more objective results.

Acknowledgements

The authors would like to thank A. McBratney, D. Dent and A. Van Wambeke for their critical review of the paper.

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