Modellistic Approach for Land Suitability - An Application to Maize

M. Wahsha[1*], Anas. M. Al-Omari[2], K. Mostafavi[3], Bassem M. Raafat[2&8], M. Ghotbi[4], M. Ghotbi[5], H. R. Rouhi[6] M. Esmaeili Azad[5], M. Ramezani[5], M. Amini Dehaghi[7], A. Moghaddam Khamseh[7]

[1] Department of Environmental Sciences, Ca' Foscari University of Venice, Italy
[2] College of Applied Medical Science, Taif University, KSA.
[3] Department of Agronomy and Plant Breeding, Karaj Branch, Islamic Azad University, Karaj, Iran.
[4] Department of Ecology and Natural Resources Management, Faculty of Agriculture, University of Bonn, Germany.
[5] Faculty of Agriculture and Natural Resources, Islamic Azad University, Iran.
[6] Department of Horticulture, Faculty of Agriculture, University of Guilan, Iran.
[7] Department of Agronomy, Faculty of Agriculture, Shahed University, Iran.
[8] Genetic Engineering and Biotechnology Division, NRC, EGYPT
[*] dr.mohammadwahsha@yahoo.com; omari_anas_2@yahoo.com

Abstract: Land suitability classification is currently based on the definition of a Land Utilisation Type, the compromise point between environmental sustainability and economic sustainability. The Simulation methods to define Land Utilization Type have been relatively little used since mathematical models are focused on problems of scientific rather than practical nature. In this paper a regression model is presented as a tool in prediction of crop production. The model is based on the relationships among climatic conditions, soil water, nutrient concentration in plants, and maize production. Climatic condition is modelled by the aridity index and is linked to crop production by a Gauss curve, soil water is modeled by AWC (available water capacity), which is linearly correlated to crop production. Finally, nutrients concentration is linked to crop production by a non rectangular hyperbole. Jointing the three modules (climate, water, and nutrients) originates a complex theoretical equation, in which all chemicals absorbed by plant are considered. The model has been validated in experimental trials. Its current application is subjected to a simplification of the theoretical equation.

[M. Wahsha, Anas. M. Al-Omari, K. Mostafavi, B. Raafat, M. Ghotbi, M. Ghotbi, H. R. Rouhi, M. Esmaeili Azad, M. Ramezani, M. Amini Dehaghi, A. Moghaddam Khamseh. **Modellistic Approach for Land Suitability An Application to Maize.** J Am Sci. 2012; 8(5):139-149]. (ISSN: 1545-1003). http://www.americanscience.org. 19

Key words: Land suitability, Modellistic approach.

1. Introduction

Soil is a scarcely renewable resource, fundamental for survival and development of human population **(Chesworth, 2008).** Matching the use of soil with current desertification processes and population increase, has risen the question of the possibility of an exhaustion of the productive capacity of soils, and the need to manage this resource: i) in its original features, ii) with variations introduced by a specific use of soil (typically a cultivation), and iii) looking at the economic relevance that specific use has **(Richter and Markewitz, 2001).** In this perspective, in 1976, the FAO formalized the Land Suitability classification. Land Suitability is the fitness of a given type of land for a defined use; its classification is based on the definition of a Land Utilization Type, i. e. the best use suggested by the classification, that represents the compromise point between environmental sustainability and economic sustainability.

There are three ways to define the Land Utilisation Type: direct measurement; empirical assessment based on assumed relationships between benefits and diagnostic criteria; and simulation methods using mathematical models.

The first procedure is based on the measurement of the actual crop production and on the reference of the actual production to the regional average production. If the production measured is less than the average, that particular area is classified as not suitable for the cultivation considered.

The second procedure is carried out by construction of a conversion table, in which diagnostic criteria (soil characteristics and land qualities) are related to different classes of land suitability **(Fao, 1976; Beek, 1978).**

To date, the third procedure has been used relatively little **(Matthews and Stephens, 2002)**, since "it is widely accepted that a major reason for poor model adoption in DSSs (Decision Support Systems) is linked to the undue emphasis of many models on problems of a scientific rather than a practical nature, resulting in failure to address the problems that the decision makers are facing".

Since many environmental data are presently available in geographic information systems, it is easy to process data on land characteristics through models to specify just which combinations of attributes are required for any given purpose.

In this study we present a mathematical model based on environmental key properties, with the aim of defining complex land qualities and suitability classes, and to predict crop production.

2. Materials and Methods:

Materials:

The data used for the development of the model have been deduced from a study on the effects of micronutrients on the yield of crops particularly important for the economy of the developing countries **(FAO, 1996).**

The study considered various crops (wheat, barley, soybean, cotton). Since most of the data recorded were related to maize, we focused our attention on sites cultivated with maize. Eight sites from different developing countries, included in the FAO study, were selected. Each site had homogeneous soil features (texture, pH, cation exchange capacity (CEC) and organic matter content) and was divided in nine plots: the first one was not fertilized, the second was fertilized with Nitrogen, Phosphorus and Potassium (NPK), the third was fertilized with NPK plus micronutrients (Ca, Mg, B, Fe, Mn, Mo, Zn), the remaining plots were fertilized with the "minus one" design. The data used to develop the model are presented in Tables 1 and 2.

Table 1: Nutrient concentration in maize (N, P, K, Ca and Mg are in % d.w.; B, Cu, Fe, Mn, Zn are in mg/kg) and crop yield (kg/ha) in different developing countries (source: Sillanpaa, 1990).

Site	N	P	K	Ca	Mg	B	Cu	Fe	Mn	Zn	Yield
Kabwe (Zambia)	2.02	0.406	2.39	0.26	0.15	8.6	7.2	82	91	17.7	2156
Rawat (India)	2.62	0.186	1.76	0.55	0.32	4.7	12.4	203	75	15.4	667
Nkhata Bay (Malawi)	2.83	0.335	3.76	0.36	0.27	3.2	11.4	128	78	15.2	801
Tepic (Mexico)	3.22	0.358	3.59	0.34	0.23	9.4	11.5	237	135	40.9	2120
Zomba (Malawi)	2.21	0.368	3.03	0.35	0.12	3.1	6.9	189	67	12.5	1061
Kananga (Philippines)	2.80	0.173	2.69	0.26	0.11	4.7	13.3	144	264	42.1	1997
Guadalajara 1 (Mexico)	8.39	0.361	2.62	0.32	0.14	5.8	10.1	151	509	30.4	8670
Guadalajara 2 (Mexico)	3.29	0.308	3.01	0.33	0.14	4.4	9.3	221	552	39.7	4570

Table 2 – Selected soil properties in different developing countries (source: Sillanpaa, 1990).

Site	Clay %	Silt %	CEC cmol/kg	Organic Carbon %
Kabwe (Zambia)	6	13	5.1	0.5
Rawat (India)	28	67	23.1	0.4
Nkhata Bay (Malawi)	17	14	13.4	1.3
Tepic (Mexico)	3	25	6.9	0.7
Zomba (Malawi)	20	17	14.5	0.8
Kananga (Philippines)	31	11	11.7	1.0
Guadalajara 1 (Mexico)	31	52	16.6	1.5
Guadalajara 2 (Mexico)	8	40	9.3	1.1

Methods

The structure of the model may be expressed with the equation

(2.2.1) P = f (climate, water, nutrients).

Where P is the crop production, climate is expressed as mean annual temperature and precipitation, water is the amount of water readily available for plants and nutrients represent the nutrients concentration in plant. The three factors may be accounted for as the most important in physiological processes.

To develop this kind of model a multiple regression with a large data set is required. Giving the model a multiplicative structure, equation (2.2.1) can be expressed as:

$P = f1\ (climate)*f_2\ (water)*f_3\ (nutrient)$.

Of the three functions reported in equation (2.2.2), f3 (nutrient concentration) is known in the literature as a not rectangular hyperbole **(Adams *et al.,* 2000)**, f2 (water availability) is known as a linear **function (FAO, 1983; Donatelli *et al.,* 1998)**, while f1 (climate) is not available in the literature, but is easy to obtain. Therefore, the (2.2.2) is simplified to a single regression of the function f1.

3. Modeling Physiological Processes:

Climatic Conditions:

To describe the climatic conditions we used the Aridity Index, i.e. the ratio between potential evapotraspiration and mean annual precipitation **(Arora, 2002):**

ETP is expressed using a cubic relationship with mean annual temperature **(Turc, 1961)**:

$$(3.1.1) \qquad AI = \frac{ETP}{P}$$

ETP = 300 + 25T + 0.05T3

$$(3.1.2) \quad AI = \frac{300 + 25T + 0.05T^3}{P}$$

By substituting the Turc formula for ETP in equation (3.1.1) we obtain:

This equation computes the aridity index (AI) as a function of mean annual temperature and means annual precipitation, data that are easily available or measurable. The climatic data utilized in the present study were obtained from **Rohk (2009)** and are reported in Table 3.

Table 3 - Mean annual temperature (maT), mean annual precipitation (maP) and calculated Aridity Index (AI) of selected sites in different developing countries. Data are computed as an average of 21 years of observation.

Site	m.a.T (C°)	m.a.P (mm)	AI
Kabwe (Zambia)	20,1	907	1,330872
Rawat (India)	20,9	860	1,488926
Nkhata Bay (Malawi)	23,2	1657	0,91001
Tepic (Mexico)	20	1252,22	0,958298
Zomba (Malawi)	21,1	1343,66	0,966179
Kananga (Philippines)	23,6	1602,3	0,96788
Guadalajara (Mexico)	19,7	919,48	1,283861

3.2 Soil Water:

We considered the amount of water that is readily available for plants: the available water capacity (AWC), i.e. the amount of water included between field capacity (FC) and permanent wilting point (PWP) as:

$$(3.2.1) \quad AWC = FC – PWP.$$

Since the capacity of soils to retain water is conditioned by texture, organic carbon (OC) and cation exchange capacity (CEC), FC and PWP can be expressed, in terms of soil features, by two equations developed by **(Tombesi *et al.*, 1980)**:

FC = 7.752 + 0.299 CEC + 0.167 CLAY + 0.187 SILT +1.909 Org. C

PWP = -1.420 + 0.271 CEC + 0.127 CLAY + 0.163 SILT + 1.535 Org. C.

By substituting in equation (3.2.1) the terms of equations (3.2.2) and (3.2.3), we obtain

(3.2.4) AWC = 9.172 +0.028 CEC + 0.04 CLAY + 0.024 SILT + 0.374 Org. C

3.3 Nutrient Concentration in Plant:

Crop production presents several phases related to nutrient concentration. Considering a generic nutrient i, it is possible to define a percentage of the maximum yield we may have in a particular environment and under a certain climatic condition **(SWMCN, 2009).**

At low nutrient concentration (Fig. 1), the crop production presents a first phase with production percentage less than 75% of the potential maximum yield **(Adams *et al.*, 2000).** A second phase, where the yield ranges between 75% and 95%, is known as “hidden hunger”. The third phase, where the yield ranges between 95% and 100%, is defined as optimal. Beyond the optimal phase, the yield attains a constant level. This corresponds to the “luxury uptake” phase, when the plant continues to absorb nutrients, but there is no increase in production. Finally, i is present in plants in such a high concentration (excess) that there is evidence of toxicity, and production collapses **(Schulte and Kelling, 1986).**

The curve reported in fig. 2 may be considered as the union of two different non rectangular hyperbola (NRH), as proposed by **(Kovalik and Sanesi, 1980)**. According to these authors, NHR is expressed by the equation:

$$(3.3.1) \quad Y = \frac{(Ax+q) - [(Ax+q)^2 - 4Axq(1-F)]^{1/2}}{2}$$

where Y is the yield percentage linked to a specific nutrient and x is the nutrient concentration in plant; A is the angular coefficient of oblique asymptote, q is the saturation level and F represents the distance between the NRH and its asymptotes. This equation describes the yield percentage for nutrient concentrations ranging between 0 and the optimum concentration.

It is possible to find out the NRH equation from nutrients optimum to excess using an indirect approach. The asymptotes of NRH equation are:

$$\left[\frac{q - Y}{q}\right] = F \quad ; \quad \left[\frac{Ax - Y}{Ax}\right] = F$$

In the NRH describing nutrient concentration from optimum to excess, the oblique asymptote has a different solution: A assumes a negative value and a new parameter m, that represents the origin ordinate of the asymptote (Figure 3), must be introduced. In this case, therefore, the equation (3.3.1) is transformed into the equation:

$$(3.3.2) \quad Y = \frac{(Ax + m + q) - [(Ax+m+q)^2 - 4(Ax+m)q(1-F)]^{1/2}}{2}$$

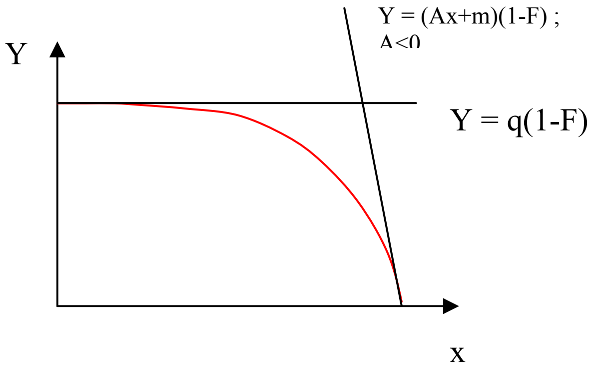

Fig. 3: graphical representation of the range between optimum and excess NRH: the oblique asymptote has a different equation, this leads to a different form for the equation.

The equation (3.3.1) is described by three parameters (A, q, F), while equation (3.3.2) is described by four parameters.

In order to calibrate the equation (3.3.1) we applied the concentration ranges suggested by the Plant and Soil Analysis Lab in Madison, Wisconsin, U.S.A. (*Personal Communications*) (Table 4). The numerical values of the parameters A, q, F are given by the equations:

$$\begin{cases} q = (Ax-1)/(Ax - 1 - AxF) \\ F = (Z-1)(Ax-1)(Az-Z) / \overline{A(z - Axz + AxzZ} - xZ^2) \\ A = (yZ^2 - yZ + xY2Z + zY + zY^2 + xYZ^2)/(zyZ - xyZ + xyYZ + xzY - xzZY) \end{cases}$$

(where Z = 0.75; Y = 0.95; x, y, z are the concentrations related to the yield percentages).

The three factors describing physiological processes have been previously modelled by AI, AWC and NRH. Therefore, the equation (2.2.2) can be expressed as:

$P = f(AI) * AWC * \Pi iYi$

Extracting f(AI) we obtain :

$$f(AI) = \frac{P}{AWC * \Pi iYi}$$

The numerical values applied to f (AI) are reported in table 5, together with the Aridity Index. The recorded values, obtained considering that maize absorbs only the nutrients considered by **(Fao, 1983)**, may be interpolated by a Gauss curve (Fig. 4).

Table 5: numerical values for A, q, F computed starting from the concentration ranges presented by the plant and soil analysis lab.

$$(3.3.3) \quad \frac{P}{AWC * \Pi_i(Y_i)} = 1652\, e^{-51(IA-1.158)^{\wedge}2}$$

	A	q	F
N	0,48338	1,089481	0,03682
P	5,067353	1,035335	0,02065
K	0,6204724	1,0216529	0,008773
Ca	22,666667	1,64999	0,36497
Mg	8,1057	1,0275329	0,0201838
Mn	0,06708	1,03203	0,0180378
Zn	0,06708	1,03203	0,0180378
B	0,519736	1,10338	0,0891898

The Gauss curve has the equation:

$y = ae^{-b(x-c)^{\wedge}2}$

where c represents the value of AI that gives the maximum yield for maize.

In the study case, substituting f(AI) in the above equation, we obtain:

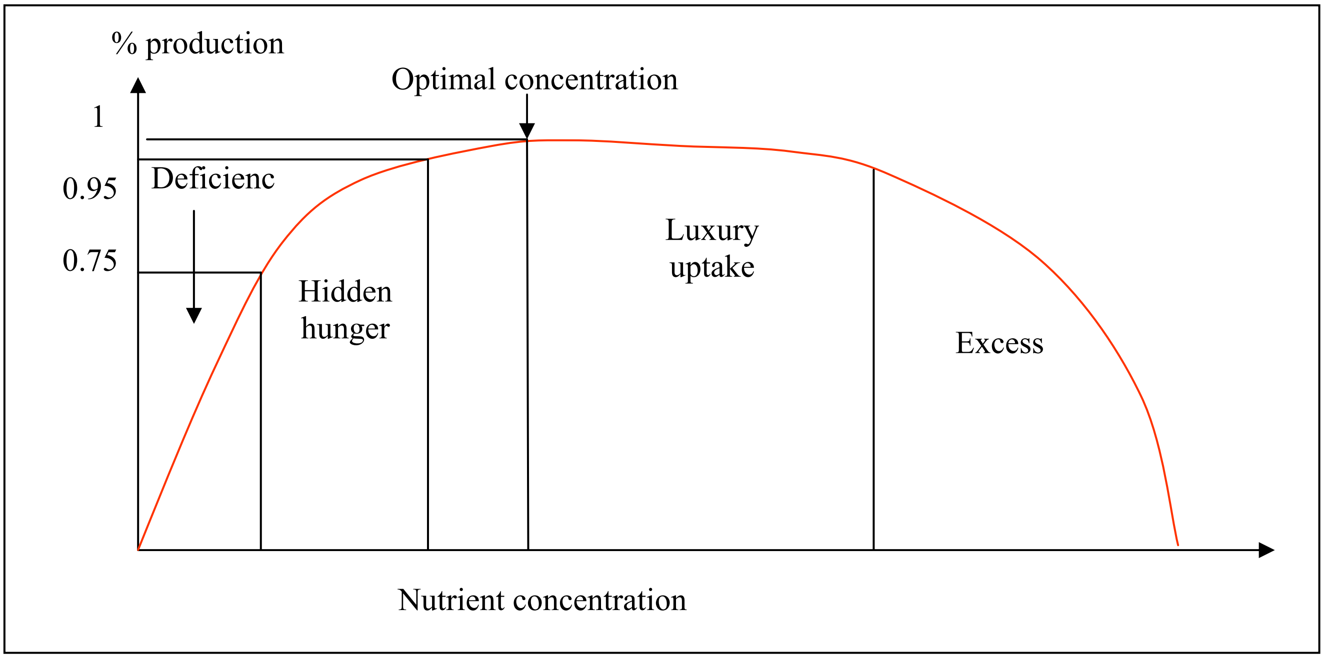

Fig. 1: graphical representation of the production ranges crossed increasing the concentration of a nutrient (modified after Schulte and Kelling, 1986).

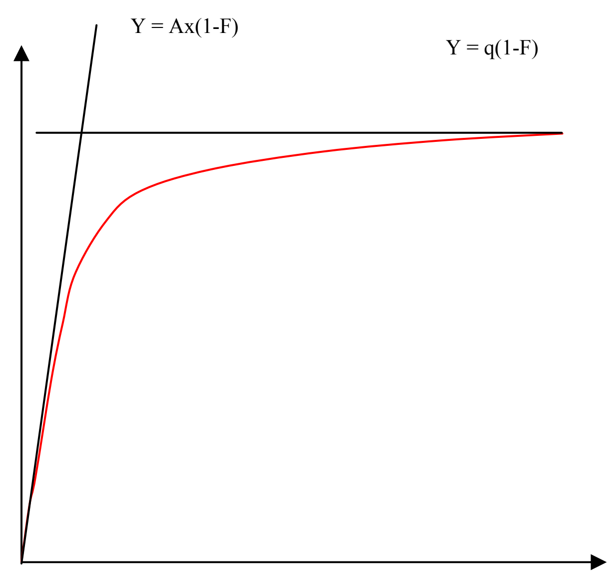

Fig. 2: graphical representation of an NRH with its asymptotes. This NRH is valid only from the concentration ranges from 0 to optimum.

Table 4: Concentration range for various nutrients as presented by the PLANT AND SOIL ANALYSIS LAB, Wisconsin University, Madison (SCHULTE and KELLING, 1986).

	CONCENTRATIONS				
NUTRIENT	deficient	low	optimal	high	Excess
N%	<1,75	1,76-2,76	2,76-3,75	>3,75	----
P%	<0,16	0,16-0,24	0,25-0,5	>0,5	----
K%	<1,25	1,25-1,75	1,75-2,75	>2,75	----
Ca%	<0,1	0,1-0,29	0,3-0,6	0,61-0,9	>0,9
Mg%	<0,1	0,1-0,15	0,16-0,5	>0,5	----
Zn ppm	<12	12,0-18,0	19,0-75,0	76-150	>150
B ppm	<2	2,0-5,0	5,1-40,0	41-55	>55
Mn ppm	<12	12,0-18,0	19,0-75,0	>75	----
Fe ppm	<10	10,0-49	50,0-250	251-350	>350
Cu ppm	----	<3	3,0-15	16-30	>30

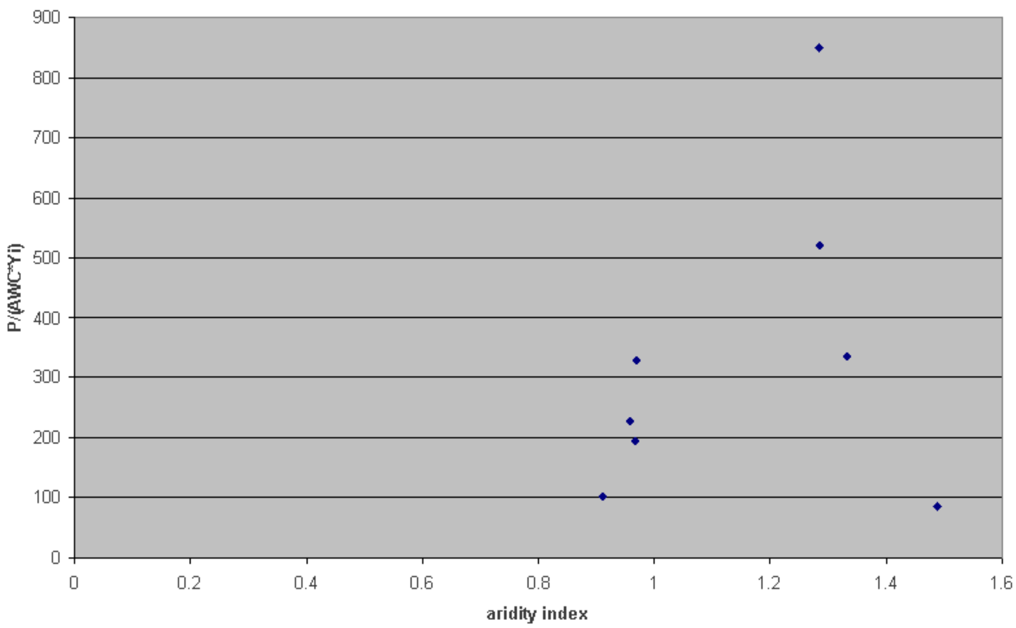

Figure 4 - plot of f(AI) versus aridity index. The term on legend P/AWC*Yi has to be intended as P/AWC* iYi (= f(IA))

4. Results and Discussion:

Unifying the three sub-models we obtain a theoretical equation to compute the maize production (4.1):

$$P = ae^{-b(AI-c)}AWC[\Pi_{i=1}^{n}(Ax+q)-[(Ax+q)^2-4Axq(1-F)]^{1/2}\,\Pi_{j=1}^{s}(Ax+q+m)-[(AX+q+m)^2-4(Ax+m)q(1-F)]^{1/2]}/2.$$

The equation (4.1) considers all the chemicals absorbed by maize, the set i representing all the nutrients, and the set j representing all the toxic elements.

The overall quantification of the model presents some problems:

the set of elements considered in the model is limited: more elements could be absorbed by maize; more information on their critical concentration is needed; The measurement of chemical elements concentration in plant requires high costs.

To avoid such problems, it is possible to include information related to the chemical status of plants, introducing in the model the "flexibility constant"(Kf). The flexibility constant was defined by **Kovalik (1978)** as "(a parameter that) describes the influence of unknown (or not controlled by the model) factors on biomass increase". Therefore, all the chemical information is included in Kf, and the equation (4.1) may be written as

(4.2) $$P = ae^{-b(AI-c)}AWC\,Kf$$

Being defined as yield percentage, Kf assumes values ranging between 0 and 1; if in equation (4.2) Kf=1, all the nutrients are present in plant in their optimal concentration and all toxic elements are not present (or present in irrelevant concentration), and the equation computes the maximum obtainable production. If Kf=0, at least one nutrient is not present in plant or at least one toxic element is present in lethal concentration, and there will not be crop production. **(Dourado-neto *et al.*, 1998)**

Concerning the application of the model, we assumed that the values of a, b, c in equation (4.1) were correct, and Kf =1. In this case we obtain the equation (4.3):

$$P = 1652Kf\,e^{-51(IA-1.158)^{2}} AWC^{*} \prod_i \left[\frac{(A_i xi+q_i) - [(A_i xi+q_i)^2 - 4A_i x_i q_i(1-F_i)]^{1/2}}{2} \right] \qquad (4.3)$$

Where i = (N, P, K, Ca, Mg, B, Fe, Mn, Zn). Computing the production from the data set we obtain the diagram reported in Fig.5.

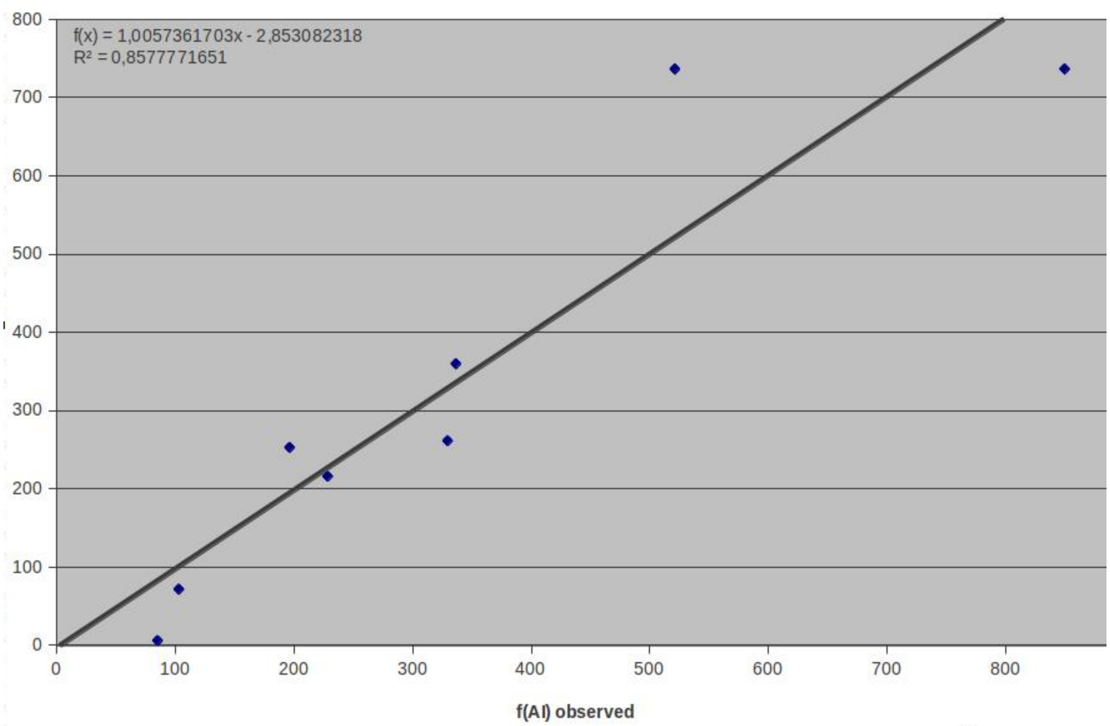

Figure 5 - observed f(AI) versus computed f(AI)

The method used is focused on the determination of the values a, b, c (Gauss curve descriptors) and, for the practical application, on the simplicity of data collecting.

AI is calculated on basic information (annual mean precipitation and temperature). In this study it derives from data sets with temperature and precipitation computed as an average of 21 years of observations (1969-1990). The effect of climatic changes was not considered.

A considerable point is the function that links production to AWC. In this study we considered the linear relationship between AWC and yield for low AWC values **(FAO, 1983).** As **Donatelli *et al.* (1998)** said: AWC is in contrast with air capacity (AC); therefore, for high AWC values there are phenomena of roots anoxia and, increasing clay percentage, difficulties for root penetration in soil. Both of them lead to a collapse in yield, and therefore, it is possible to describe the relationship between AWC and yield by a Gauss curve.

4.1 The nutrient status in plant and the flexibility constant.

The model proposed computes the maize production starting from a standard status, represented by the nutrients optimum concentration in plant.

The method used implies that these values are dependent on information about the chemical status of maize. In particular, the values computed in equation (3.3.3), depend only on the concentration of N, P, K, Ca, Mg, B, Fe, Mn, Zn, while other chemicals (e.g. Al, S, Cl…) are not considered.

The numerical values computed for A, q, F in equation (4.3) are related to the silky stage of the maize inflorescence, since in other growing stages the critical concentrations are different. A considerable point is given by the value Kf may assume, which is the nutrient status of the soil and which are the elements responsible for Kf<1.

Validation of the model

To validate the model we used data presented by (Romanin and Marizza, 1983) in an experimental trial carried out in the Agricultural Experimental Station at Udine, Italy, having the objective to determine the effects of N fertilization on maize.

Data used for the model validation concern maize fertilization with calcium nitrate $Ca(NO3)2$, and are reported in Table 6. A good fitting was recorded between the calculated and the actual maize yield in the fertilized plot, while it is lower in the not fertilized plot. Indeed, the equation (4.3) computes a maize production of 11425.7 Kg/ha in the fertilized plot, against an actual production of 11510 Kg/ha; in the check plot, the equation (4.3) computes a production of 8196.7 Kg/ha against an actual production of 6360 Kg/ha (Fig. 6).

Table 6: numerical values of aridity index and of the ratio P/AWC*ΠiYi (= f(IA))

f(AI)	AI
336,4481	1,330872
84,90697	1,488926
102,8565	0,91001
228,2956	0,958298
196,2418	0,966179
329,4405	0,96788
849,615	1,283861
521,0574	1,283861

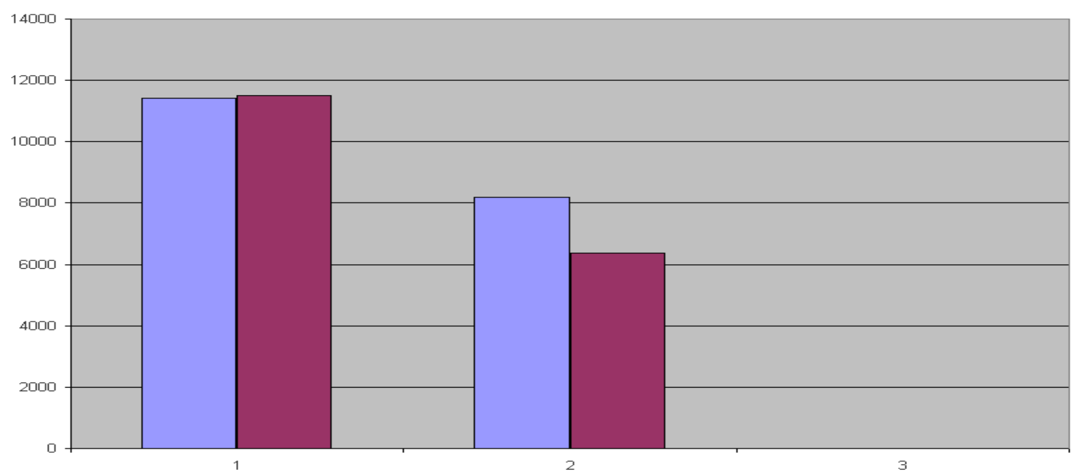

Figure 6 - observed production versus computed production in Castion delle Mura.

Plants in both the experimental plots proved to absorb the same amount of calcium (Ca fertilized = 0.9 ppm ≈ Ca not fertilized = 0.91ppm). This means that the calcium added with fertilization was not absorbed or not available to maize. Indeed, calcium may precipitate with elements like boron or sulfur. In the experimental trial the calculated maize production is higher than the observed one. This means that, in equation (4.3), Kf <1, and this may be due to an excess of B and/or S. In the presence of Ca, these would form calcium borate and/or calcium sulphate, thus reducing Ca availability to plants.

5. A possible application procedure

According to the land suitability philosophy, the Land Utilisation Type must be sustainable both from the environmental and the economic point of view. This means that every choice we make in relation to a proposed use has to consider the economic cost associated. The flow diagram shown in Figure7 indicates a possible application procedure for the model and Table 7 shows the data used for this study.

Table 7: data used for the diagram model.

sand (%)	57,99	Soil characters
silt (%)	21,85	
Clay (%)	20,16	
Organic Carbon (%)	1,39	
pH (KCl)	7,15	
CEC (meq/100gr)	14,1	
Annual precipitation (mm)	847,6	Climatic data
Annual mean temperature (°C)	16	
N (%)	3,66	Nutrients concentration in leaves At flowering in fertilised plot ($Ca(NO_3)_2$
P (%)	0,31	
K (%)	1,88	
Ca (%)	0,9	
Mg (%)	0,24	
Fe (ppm)	142	
Mn (ppm)	74	
Zn (ppm)	47	
N (%)	2,66	Nutrients concentration in leaves At flowering in check plot
P (%)	0,27	
K (%)	1,97	
Ca (%)	0,91	
Mg (%)	0,11	
Fe (ppm)	107	
Mn (ppm)	57	
Zn (ppm)	33	

In the first stage, the soil features give information on the availability of nutrients; this will reduce the range of crops that can be harvested and will determine a range of variation of Kf. Once the crop is chosen, being the model developed considering the chemical status of plant, plant-soil relationship models should be applied; this will permit to measure the chemical status of soil. If such models are not available it is necessary to measure the chemical status directly in plants: this leads to a multi-annual experimentation. When data on chemical status of plants are available it is possible to compute the maximum obtainable production (eq. 4.2) and the actual production (eq. 4.3). The two values (maximum and actual yield) should be compared to the economical sustainability of the use considered. If the maximum obtainable production results not economically sustainable, the use is classified as N (Not Suitable), because there are permanent limitations for the use considered. In this case the procedure should consider another cultivation.

If the actual production results not economically sustainable, it is possible to consider if a fertilization is economically sustainable; if so, the use should be classified as S2, otherwise it should be classified as N. If the actual production is economically sustainable, the use should be classified as S1 (Figure 7).

6. Conclusions:

The model presented may be considered a proposal for a land evaluation method based on crop yield simulation. The most attractive aspect is that, unlikely what happens with other models, it considers the micronutrients contribution, whose importance has been underestimated for long time. The application of the model showed a good response either in prediction or in finding out the problems that may arise with nutrients availability that the model does not control. However, more experimental work should be addressed to attain information on soil nutrient chemistry and on Kf definition.

Corresponding author
M. Wahsha
Department of Environmental Sciences, Ca' Foscari University of Venice, Italy
dr.mohammadwahsha@yahoo.com

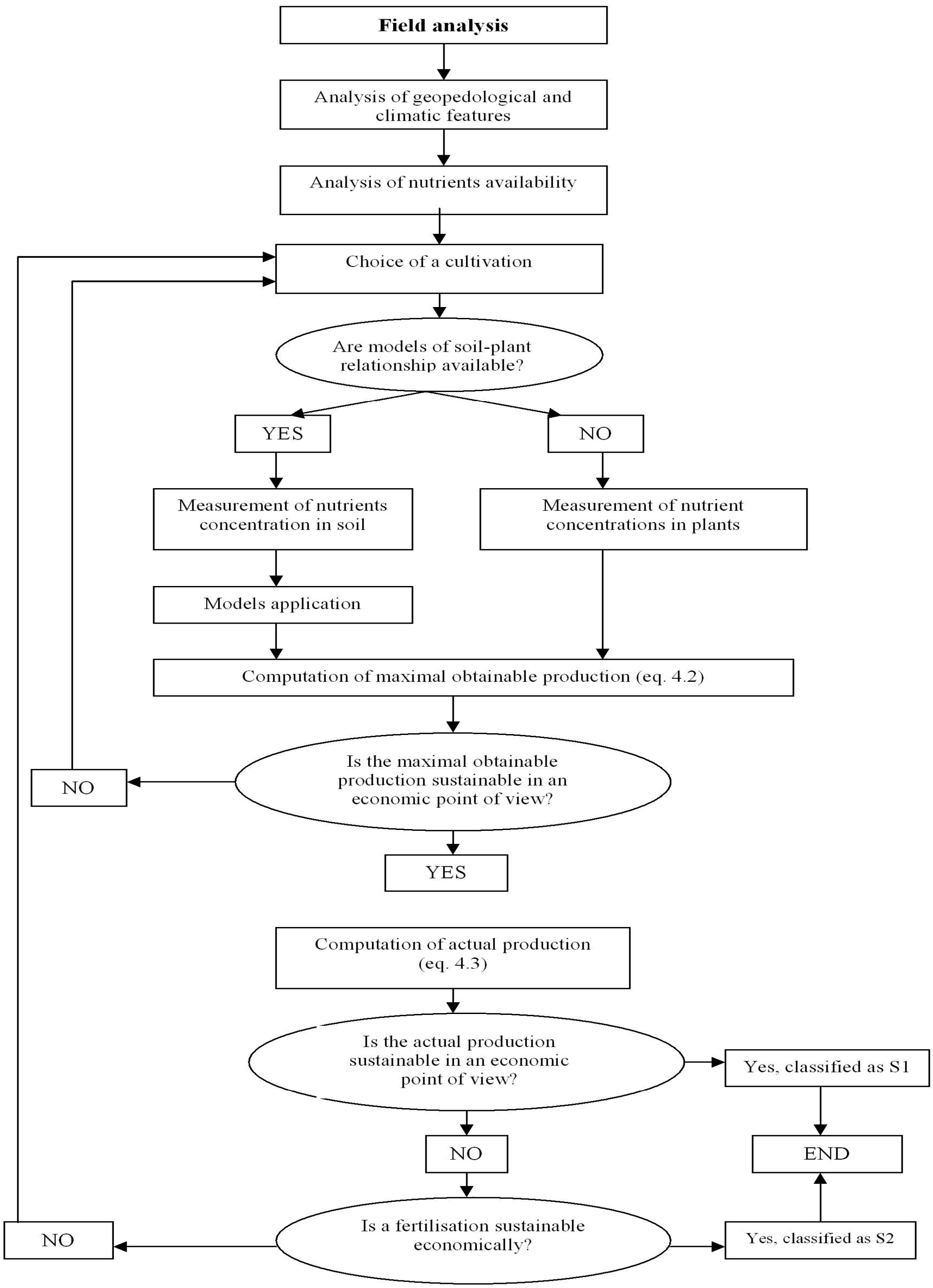

Figure 7: Diagrammatic representation of the proposed hypothesis model, including structural testing and results.

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