Research Article

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Soil productivity analysis based on a fuzzy logic system

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Abstract

BACKGROUND: Maintaining soil productivity is essential if agriculture production systems are to be sustainable. However, there is a paucity of tools for measurement for the purpose of understanding changes in soil productivity. Fuzzy logic-based analysis offers this possibility. It is a new method on the evaluation of soil productivity in Turkey and even in the world.

RESULTS: Values for pH, salinity, carbonate and organic matter were entered into the system as input variables so as to obtain soil productivity as the output. After the membership functions related to input and output were determined, rules were created. Then, the fuzzy logic system was applied separately to pH, salinity, lime and organic matter values of different soil types present in the Kocaeli region with the aim of obtaining corresponding fuzzy values. Thus, soil productivity profiles of the region were deciphered.

CONCLUSION: Organic matter levels in the study field remained below 30 g kg^{-1} and varied between 22 and 28 g kg^{-1}. Productivity values were obtained as a percentage and varied between 16.9% and 18.1%. The lime content of the study soils varied in the range of 33–88 g kg^{-1}. Average totals for salt values of the field changed between 0.58 and 0.77 g kg^{-1}.

Keywords: fuzzy logic; pH; soil productivity; soil classification; salinity

INTRODUCTION

Soils in Turkey have high clay and lime contents due to the temperature, geographical location and geological structure. Soils are poor and organic matters and some soil structures are damaged. The effects of such physical, chemical and biological damage in soil structure might be dramatic and lead to nutrient deficiency which occurs when the nutrient is not in sufficient quantity to meet the needs of the growing plant.[1]

Since intensive cultivation methods are used in Turkey, specifically in central Anatolia, south-eastern Anatolia, Çukurova and the Aegean regions, a lack of beneficial nutrient elements has been recorded. Some soils are even known to suffer from serious nutrient element deficiencies. Such deficiency is mainly observed in the Marmara region (in the soils of Kocaeli Province and its surrounding area).

The problem of 'soil productivity' in Turkey can be defined as a 'deficiency in nutrient elements in large portions of the soils due to high lime and clay content of the main matter; high pH values, soil structure, decomposition of organic matter and, low organic matter content'.[1]

Soils with dark surface horizons generally have higher organic matter content and are appropriate for the cultivation of plants.[2] Organic matter plays an important role in the formation of soil structure, providing aeration of the soil and keeping nutrient elements along with their high cationic exchange capacity.[3] Organic matter was studied by Guppy *et al*.[4] and Clemente *et al*.[5]

Soil pH has direct and indirect effects on the other chemical, physical and biological characteristics of the soil. Therefore, it has a special role among the factors effecting soil productivity. pH has a significant effect on the formation of clay minerals in the soil and is one of the most important soil properties that affects the availability of nutrients.[6] Variables of pH were studied by Summer *et al*.[7]

Salts may accumulate, leading to naturally saline soils and interfere with plant cultivation. Sodicity and salinity occur simultaneously in many soils. These soil constraints may be salinity, alkalinity and acidity.[8] The significance of the threshold and turbidity concentrations in relation to sodicity and microstructure has been investigated by Quirk.[9]

Lime is an important factor for increasing pH values (particularly of acid soils) to the levels optimum for plant cultivation. Lime increases soil microorganism activity and speeds up mineralisation of the organic matters.[8] Lime and its relation to the soil were studied by McBeath *et al*.[10] and McKenzie *et al*.[11]

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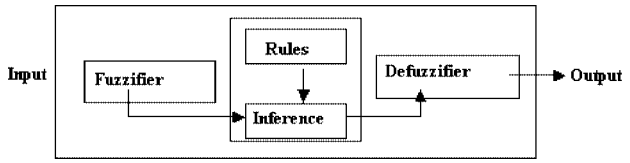

Figure 1. A fuzzy logic system.

Alluvial soils are young soils generally formed on young sediment deposits. Matters constituting such type of soil are carried and accumulated by rivers. Colluvial soils are, on the other hand, young profile soils which are carried by gravity, landslide, surface run-offs or lateral rivers from short distances, accumulated in the skirts of vertical steep slopes and formed on 'colluvial' matter.[12–14]

Brown forest soils are formed on main matter having a high lime content. Such soils are generally formed under deciduous forest cover. They have high agricultural productivity. Low levels of podzolisation and calcification play an important role in the formation of lime-free brown forest soils. These soils are redder and acid formation can be observed not only on the main matter but also on the limestone.[12–14]

Rendzina soils are classified under the calcimorphic group of interzonal soils. Therefore, the main matter, having high lime content, determines all characteristics of these soils. They are dark in colour and show alkali or neutral reactions. Organic matter and mineral matter are mixed well in this type of soil type. Regasolic soils are considered young soils due to their development.They are formed from deep, loose and soft mineral deposits.[12–14]

This study analyses soil productivity using a fuzzy logic system. Fuzzy logic is all about the relative importance of precision: How important is it to be exactly right when a rough answer will do? Lotfi A. Zadeh, a professor at the University of California at Berkeley, was the first to propose a theory of fuzzy sets and an associated logic, namely fuzzy logic.[15] Essentially, a fuzzy set is a set whose members may have degrees of membership between 0 and 1, as opposed to classical sets where each element must have either 0 or 1 as the membership degree. If 0, the element is completely outside the set; if 1, the element is completely in the set. As classical logic is based on classical set theory, fuzzy logic is based on fuzzy set theory.

As Lotfi Zadeh, who is considered to be the father of fuzzy logic, once remarked: 'In almost every case you can build the same product without fuzzy logic, but fuzzy is faster and cheaper'.[16] Fuzzy logic is based on natural language. The basis for fuzzy logic is the basis for human communication. This observation underpins many of the other statements about fuzzy logic. In 'two-valued logic', a proposition is either *true* or *false*, but not both. The 'truth' or 'falsity' which is assigned to a statement is its *truth-value*. In fuzzy logic a proposition may be true or false or have an intermediate truth-value, such as maybe true.[17]

The first industrial application of fuzzy logic was in the area of fuzzy controllers. It was done by two Danish civil engineers, L.P. Holmblad and J.J. Østergaard, who developed a fuzzy controller for cement kilns during the 1980s at the company F.L. Schmidt. Their results were published in Holmblad and Østergaard.[18]

The second wave of fuzzy logic systems started in Europe in the early 1990s, namely in the area of information systems; in particular, in databases and information retrieval.

In Fig. 1, a block diagram of a fuzzy logic system is shown. The system has four basic units. These are named as fuzzification, defuzzification, rules and inference units which are explained below:

The fuzzification comprises the process of transforming crisp values into grades of membership for linguistic terms of fuzzy sets. The membership function is used to associate a grade to each linguistic term. A membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. The most commonly used membership functions are trapezoidal, sigmoid, Gaussian *etc.* The Rule unit has several fuzzy rules that are defined by an expert. Fuzzy rules may be expressed in terms such as ''If the room gets hotter, spin the fan blades faster'' where the temperature of the room and speed of the fan blades are both imprecisely (fuzzily) defined quantities, and ''hotter'' and ''faster'' are both fuzzy terms. Fuzzy logic, with fuzzy rules, has the potential to add human-like subjective reasoning capabilities to machine intelligences, which are usually based on bivalent Boolean logic.[19] The inference unit applies the fuzzy values into the rules. Defuzzification is the process of producing a quantifiable result in fuzzy logic. Typically, a fuzzy system will have a number of rules that transform a number of variables into a 'fuzzy' result, that is, the result is described in terms of membership in fuzzy sets. There are many different methods of defuzzification available, like center of gravity, mean of maxima *etc.*

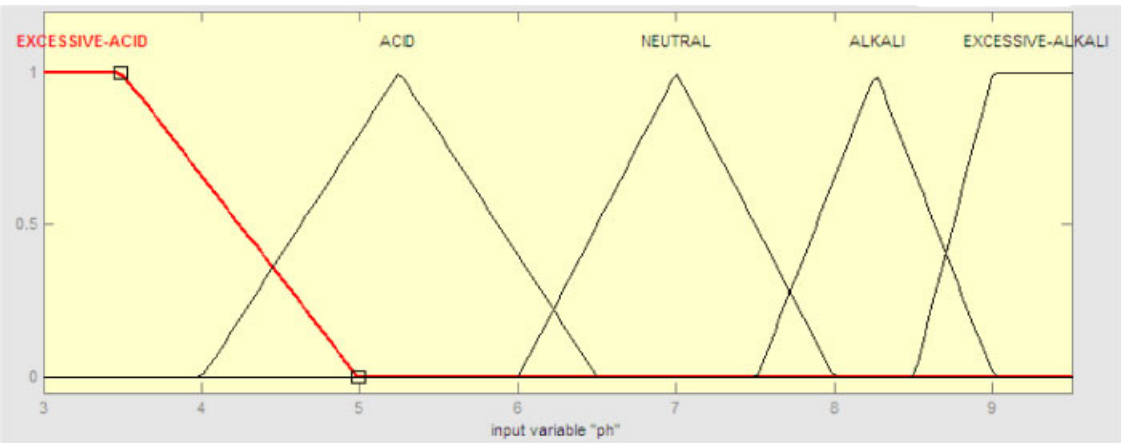

Figure 2. The membership function of pH.

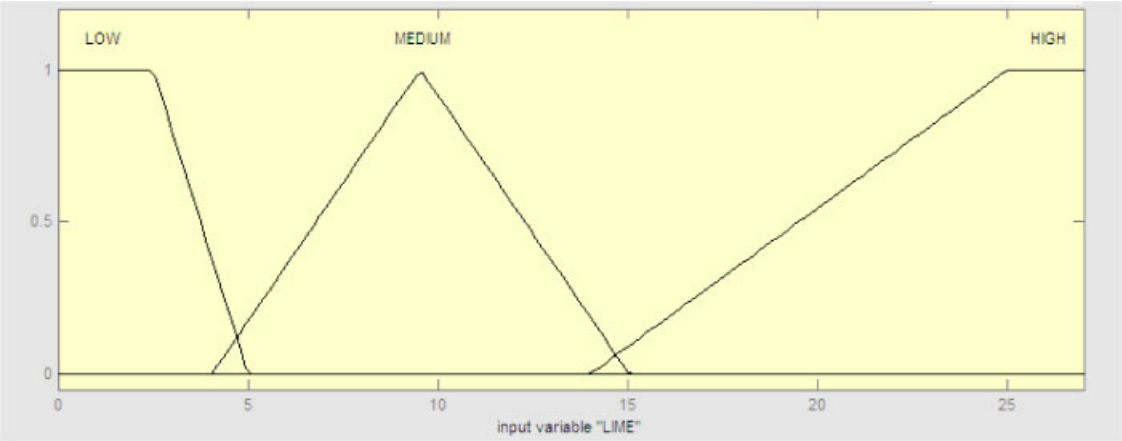

Figure 3. The membership function of lime.

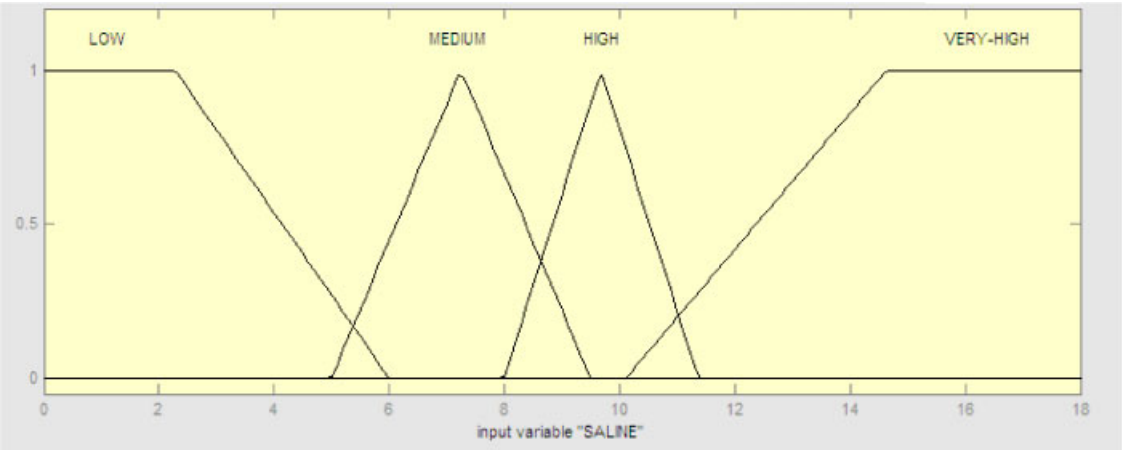

Figure 4. The membership function of saline.

Schmidt *et al*. studied soil-landscape models by using spatial modelling techniques and fuzzy classification in New Zealand. They studied typical soil profiles and soil properties using analysis of field soil samples with fuzzy logic methods.[20]

MATERIALS AND METHODS

Materials

Kocaeli Province is located in the Marmara region of Turkey, in the north-western part of Anatolia. Kocaeli Province is surrounded by mountains to the north and south. The city lies on a plain between Izmit Bay and Sapanca Lake. Mountains – the height of which varies between 300 and 600 m – are separated from each other by valleys. Kocaeli Province has a transition climate between a Mediterranean type and a Black Sea type, where summers are hot and dry while winters are cool and rainy. The highest average temperature has been recorded as 29.2 °C in July and the lowest average temperature as 3.3 °C in February. The highest average number of rainy days has been recorded as 17.2 in January.

Methods

Analysis results of specific productivity parameters of the soil samples collected from Central, Gebze, Gölcük, Kandıra and Karamürsel districts of Kocaeli Province were used in this study. pH, total salt, lime and organic matter – the factors that have direct effects on productivity – were taken into consideration in the soil analysis. Analyses were made on alluvial soil, colluvial soil, brown forest soil, lime-free brown forest soil, Rendzina soil and Regosal soil samples. Evaluation of all results from the analysis was tried within the fuzzy logic system by considering the mean values based on cumulative provincial level.

After deciding on the membership functions and rules of the system (the input and output variables of which were determined), pH, salinity, lime and organic matter values of different soil types were entered into the system as input data to obtain corresponding fuzzy values. These values reflect the productivity percentage of the soil.

The fuzzy logic system was developed by using MATLAB Release13. Steps taken in this process are defined below.

Variables

Input and output variables of the system were determined. Since they are the factors directly affecting the productivity of the soil, pH, salinity, lime and organic matter values were determined as input variables and productivity as the output variable.

Membership functions

Membership functions and limit values related with input and output variables were defined. Membership functions determined

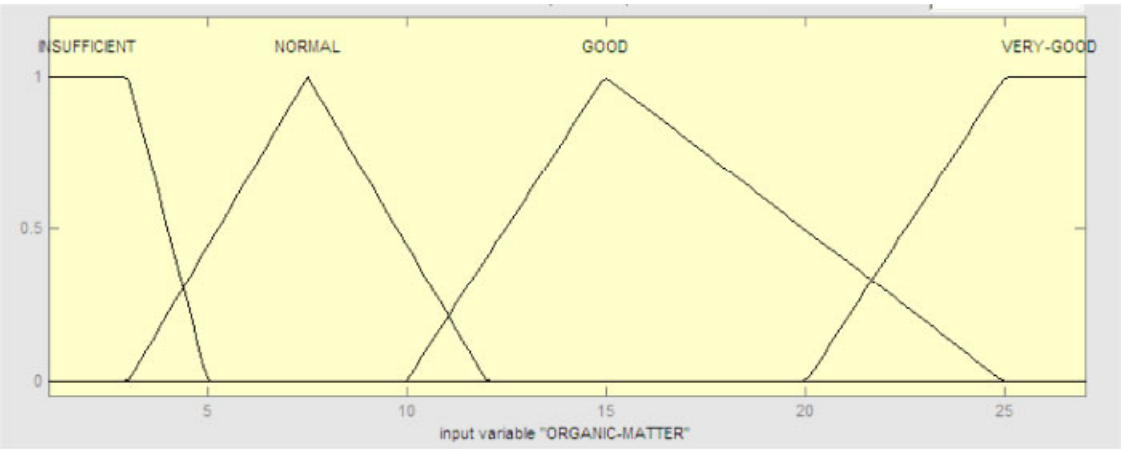

Figure 5. The membership function of organic matter.

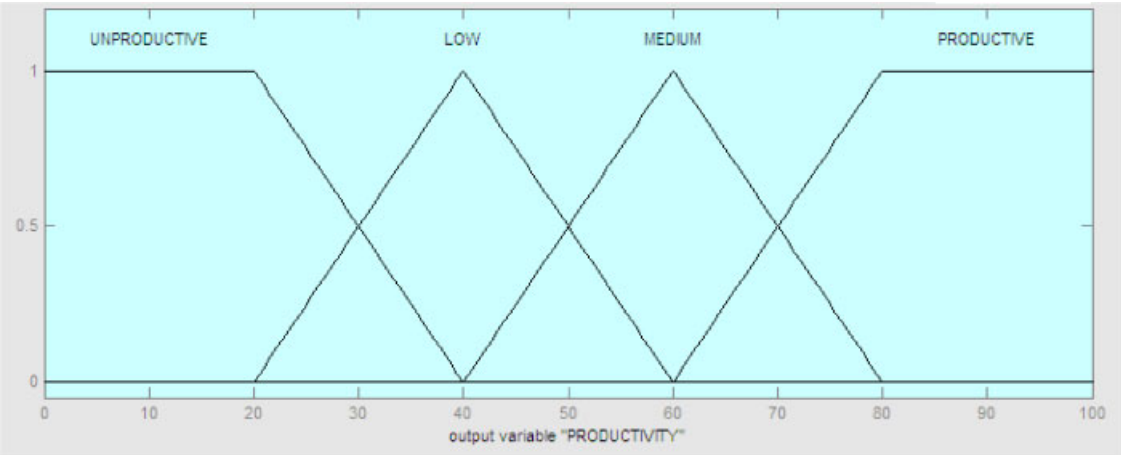

Figure 6. The membership function of productivity.

on the basis of such data are listed separately in Figs 2, 3, 4, 5 and 6. For instance, possible values of the input variable 'pH' are expressed in terms of five membership functions. Two of the five membership functions were trapezoids and the remaining three were triangles.

Rules

Rules were defined on the basis of the created membership functions. Rules were defined for the determination of the possible output in line with the interaction between input variables. Figure 7 presents a part of such rules: 'IF A THEN B'. Figure 8a and b is a three-dimensional (3-D) presentation of these rules. Figure 8a gives a 3-D presentation of the rules showing the changes recorded in productivity, lime and organic matter on the basis of the interaction between them and Fig. 8b that of the rules showing the changes recorded in productivity, pH and salt on the basis of the interaction between them. The system evaluates four input variables and one output variable together; however, the 3-D presentations show only the rules related to the selected three variables.

1. If (ph is EXCESSIVE-ACID) and (LIME is LOW) and (SALINE is LOW) and (ORGANIC-MATTER is INSUFFICIENT) then (PRODUCTIVITY is UNPRODUCTIVE) (1)
2. If (ph is EXCESSIVE-ACID) and (LIME is MEDIUM) and (SALINE is MEDIUM) and (ORGANIC-MATTER is NORMAL) then (PRODUCTIVITY is LOW) (1)
3. If (ph is NEUTRAL) and (LIME is MEDIUM) and (SALINE is MEDIUM) and (ORGANIC-MATTER is NORMAL) then (PRODUCTIVITY is LOW) (1)
4. If (ph is NEUTRAL) and (LIME is HIGH) and (SALINE is HIGH) and (ORGANIC-MATTER is VERY-GOOD) then (PRODUCTIVITY is LOW) (1)
5. If (ph is NEUTRAL) and (LIME is HIGH) and (SALINE is HIGH) and (ORGANIC-MATTER is GOOD) then (PRODUCTIVITY is LOW) (1)
6. If (ph is NEUTRAL) and (LIME is HIGH) and (SALINE is VERY-HIGH) and (ORGANIC-MATTER is VERY-GOOD) then (PRODUCTIVITY is UNPRODUCTIVE) (1)
7. If (ph is ALKALI) and (LIME is LOW) and (SALINE is LOW) and (ORGANIC-MATTER is INSUFFICIENT) then (PRODUCTIVITY is LOW) (1)
8. If (ph is ALKALI) and (LIME is MEDIUM) and (SALINE is MEDIUM) and (ORGANIC-MATTER is NORMAL) then (PRODUCTIVITY is MEDIUM) (1)
9. If (ph is ALKALI) and (LIME is HIGH) and (SALINE is HIGH) and (ORGANIC-MATTER is GOOD) then (PRODUCTIVITY is LOW) (1)
10. If (ph is ALKALI) and (LIME is HIGH) and (SALINE is VERY-HIGH) and (ORGANIC-MATTER is VERY-GOOD) then (PRODUCTIVITY is UNPRODUCTIVE) (1)
11. If (ph is EXCESSIVE-ALKALI) and (LIME is LOW) and (SALINE is LOW) and (ORGANIC-MATTER is INSUFFICIENT) then (PRODUCTIVITY is LOW) (1)
12. If (ph is EXCESSIVE-ALKALI) and (LIME is MEDIUM) and (SALINE is MEDIUM) and (ORGANIC-MATTER is NORMAL) then (PRODUCTIVITY is MEDIUM) (1)
13. If (ph is EXCESSIVE-ALKALI) and (LIME is HIGH) and (SALINE is HIGH) and (ORGANIC-MATTER is GOOD) then (PRODUCTIVITY is MEDIUM) (1)
14. If (ph is EXCESSIVE-ALKALI) and (LIME is HIGH) and (SALINE is VERY-HIGH) and (ORGANIC-MATTER is VERY-GOOD) then (PRODUCTIVITY is LOW) (1)
15. If (ph is EXCESSIVE-ALKALI) and (LIME is MEDIUM) and (SALINE is MEDIUM) and (ORGANIC-MATTER is GOOD) then (PRODUCTIVITY is PRODUCTIVE) (1)
16. If (ph is EXCESSIVE-ALKALI) and (LIME is MEDIUM) and (SALINE is MEDIUM) and (ORGANIC-MATTER is VERY-GOOD) then (PRODUCTIVITY is PRODUCTIVE) (1)
17. If (ph is ACID) and (LIME is LOW) and (SALINE is LOW) and (ORGANIC-MATTER is INSUFFICIENT) then (PRODUCTIVITY is LOW) (1)
18. If (ph is ACID) and (LIME is HIGH) and (SALINE is HIGH) and (ORGANIC-MATTER is GOOD) then (PRODUCTIVITY is LOW) (1)

Figure 7. A part of the rules of the system.

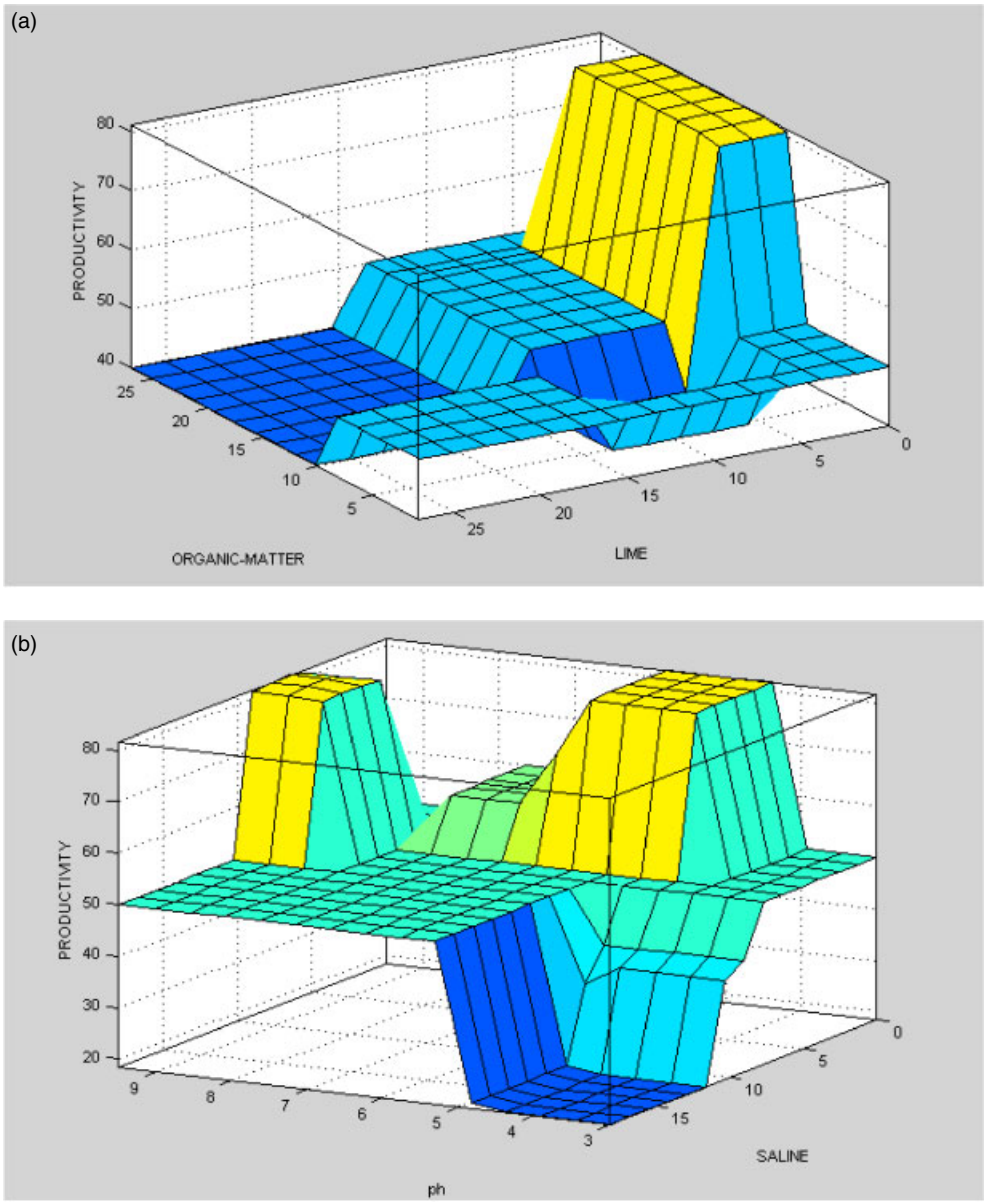

Figure 8. (a) Three-dimensional presentation of the rules relating to the selected three variables. (b) Three-dimensional presentation of the rules relating to the selected three variables.

Mean values

Provincial mean values in Tables 1, 2 and 3 were entered as 'input values' into the fuzzy logic system (the membership functions and rules of which were determined in the earlier steps) so as to obtain corresponding productivity values. The productivity values obtained this way are presented in Tables 4, 5 and 6.

RESULTS AND DISCUSSION

This study aimed at developing the general soil productivity profile of different types of soils present in Kocaeli Province via a fuzzy logic system, on the basis of the mean analysis values of pH, salinity, lime and organic matter factors (Tables 1, 2 and 3). Despite the fact that many factors exist which are effective for soil productivity, the system was structured in such a way as to accept only the values of pH, salinity, lime and organic matter content factors as input data. In general terms, there are many parameters affecting the productivity of soil; however, any fuzzy logic system and its rules should be restricted in some way as the system permits a limited number of input variables and rules. Analysis values of different soil types were entered as input data into the four-input and one-output system so as to calculate productivity values. Productivity values were obtained as a percentage and varied between 16.9% and 18.1%. Lime-free brown forest soil was found to be the most productive soil (18.1%). Colluvial soil, brown forest soil and rendzina soil produced the same productivity value (16.9%). These values are presented in Tables 4, 5 and 6.

An important part of soil organic matter is composed of colloidal matter that has a high cation exchange capacity. Therefore, it plays an important role in retaining nutrient matter that is present in the soil or fed into the soil via fertilisers. It prevents not only the sudden changes in pH value of the soil but also any possible soil damage caused by an excessive amount of salt. The level

Table 1. Results of analysis as mean of alluvium and colluvium soils[25]

	Alluviam soils				Colluviam soils			
District	pH	Total salinity (g kg^{-1})	Lime (g kg^{-1})	Organic matter (g kg^{-1})	pH	Total salinity (g kg^{-1})	Lime (g kg^{-1})	Organic matter (g kg^{-1})
Center	7.3	0.68	34	33	6.8	0.56	36	33
Gebze	7.2	0.43	69	29	7.3	0.51	135	22.2
Gölcük	7	0.72	9	31	7.2	0.65	18	26.5
Kandıra	7.3	0.65	38	23	7.5	0.63	72	25.3
Karamürsel	7.2	0.64	14	22	7.2	0.59	16	26.1
Total of provience	7.2	0.62	33	28	7.2	0.59	35	26.6

Table 2. Results of analysis as mean of brown-forest and unlime-brown forest[25]

	Brown-forest soils				Unlime brown-forest soils			
District	pH	Total salinity (g kg^{-1})	Lime (g kg^{-1})	Organic matter (g kg^{-1})	pH	Total salinity (g kg^{-1})	Lime (g kg^{-1})	Organic matter (g kg^{-1})
Center	7.4	0.69	77	32	6.9	0.52	30	27
Gebze	–	–	–	–	7.3	0.41	75	29
Gölcük	–	–	–	–	6.7	0.65	14	32
Kandıra	7.5	0.79	110	26.6	7.3	0.72	29	65
Karamürsel	7.2	0.84	59	25.7	6.9	0.62	24	23.3
Total of provience	7.4	0.77	82	28.1	7	0.58	41.6	28.1

of organic matter in the study field remained below 30 g kg^{-1} and varied between 22 and 28 g kg^{-1}. The reason behind such a low level of organic matter is the rapid decomposition of organic matter due to the hot and dry summer seasons. For this reason, farm fertilisers or green fertilisers should be preferred for the soils in this region.

Soil reaction, i.e. acidity and alkalinity level of the soil, is directly or indirectly effective on the other chemical, physical and biological characteristics of the soil. Therefore, it is one of the most important factors that determines the productivity level of the soil. pH values of the soils analysed in this study varied between 6.5 and 7.4 and they gave slightly acidic and slightly basic reactions. Generally, pH values are below alkalinity level of 8.5. Soils with pH values above 7 include high amounts of lime. The fact that the analysed soils had pH values <8.5 resulted from a low sodium effect.[21] The soil pH changes associated with the balance of cation-to-anion uptake may also be influenced by the defoliation of plants.[22] The effect is the formation of a depth interval of low pH, an acidic

Table 3. Results of analysis as mean of Rendzina and Regosal soils[25]

	Rendzina soils				Regosal soils			
District	pH	Total salinity (g kg^{-1})	Lime (g kg^{-1})	Organic matter (g kg^{-1})	pH	Total salinity (g kg^{-1})	Lime (g kg^{-1})	Organic matter (g kg^{-1})
Center	7.2	0.65	71	30	6.5	0.66	9	22
Gebze	7.7	0.65	135	30	–	–	–	–
Gölcük	–	–	–	–	–	–	–	–
Kandıra	7.4	0.61	122	27	–	–	–	–
Karamürsel	7.3	0.87	25	24	–	–	–	–
Total of provience	7.4	0.7	88	28	6.5	0.66	9	22

Table 4. Values of productivity of alluvium and colluvium soils[25]

	Alluviam soils				Colluvium soils			
	pH	Total salinity (g kg^{-1})	Lime (g kg^{-1})	Organic matter (g kg^{-1})	pH	Total salinity (g kg^{-1})	Lime (g kg^{-1})	Organic matter (g kg^{-1})
Mean of provience	7.2	0.62	33	28	7.2	0.59	35	26.6
Productivity (%)	16.6	–	–	–	16.9	–	–	–

Table 5. Values of productivity of brown-forest and unlime-brown forest soils[25]

	Brown-forest soils				Unlime brown-forest soils			
	pH	Total salinity (g kg^{-1})	Lime (g kg^{-1})	Organic matter (g kg^{-1})	pH	Total salinity (g kg^{-1})	Lime (g kg^{-1})	Organic matter (g kg^{-1})
Mean of provience	7.4	0.77	82	28.1	7	0.58	41.6	28.1
Productivity (%)	16.9	–	–	–	18.1	–	–	–

Table 6. Values of productivity of rendzina and regosal soils[25]

	Rendzina soils				Regosal soils			
	pH	Total salinity (g kg^{-1})	Lime (g kg^{-1})	Organic matter (g kg^{-1})	pH	Total salinity (g kg^{-1})	Lime (g kg^{-1})	Organic matter (g kg^{-1})
Mean of provience	7.4	0.7	88	28	6.5	0.66	9	22
Productivity (%)	16.9	–	–	–	17.4	–	–	–

subsurface layer, within the surface of 0.10 m of soil in the absence pf plants.[23]

The lime content of the study soils varied between 33 and 88 g kg^{-1}. Lime content of the soils varied within a large range. It was detected that most of these soils had high lime content. High lime content can be regarded as a problem for the agricultural productivity of the study soils. According to Slattery *et al*., alkaline soils were separated into calcareous (>50 g kg^{-1} $CaCO_3$) and non-calcareous (<50 g kg^{-1} $CaCO_3$) soils. Soil $CaCO_3$ content varied from negligible in the acidic and neutral soils to >750 g kg^{-1} in the alkaline calcareous soils.[24]

Saline soils are created with the accumulation of salt at an amount, which prevents plant cultivation. Soils with >15% exchangeable sodium rate are called 'alkali soils' or 'sodic soils'. Mean total salt value of the study field changed in the 0.58–0.77 g kg^{-1} range.

Brown forest soil and lime-free brown forest soil were found to be the most appropriate soils for agricultural production and productivity because of their high organic matter content. Rendzina and Regosal soils may be provided with additional organic matter if they are to be used for plant production. pH values of the study soils were within the limits appropriate for plant cultivation whose pH values varied in the range 6.5–7.4.

Data obtained at the end of the study will not only serve as a basis for land use plans but also facilitate solutions to possible agricultural productivity problems related with soils. Results of this study will also provide data for the future studies to be conducted in this region. Moreover, when compared with the widely used traditional productivity evaluations, analysis of productivity via a fuzzy logic system has developed a new point of view and put forward a new approach to the evaluation of productivity.

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