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Dynamic Quality Index for agricultural soils based on fuzzy logic

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ABSTRACT

The increasing number of successful applications of fuzzy logic and fuzzy sets theory to dealing with the uncertainty, imprecision and subjectivity inherent to environmental quality assessments, and the recent development of new procedures based on fuzzy logic for the design of environmental quality indexes open new ways to carry out more rigorous and realistic estimations of soil quality. With these considerations in mind, the aim of this work is to design an index based on fuzzy logic, which is especially addressed to assess the dynamic quality of agricultural soils – *Soil Dynamic Quality Index* (*S-DQI*). This index is described by a group of three indexes ($S\text{-}DQI_{PHYS}$, $S\text{-}DQI_{CHEM}$, $S\text{-}DQI_{BIOL}$), each one designed to evaluate the dynamic quality of agricultural soils with regard to their physical, chemical and biological characteristics, respectively. Each index is determined from the joint opinion of a panel of experts, which decides: (*i*) the attributes or properties of soil which determine its dynamic quality for farming; (*ii*) the most suitable indicator for quantifying each of them; (*iii*) the influence of the values taken by these indicators on the quality of agricultural soils, which is expressed by means of membership functions, and (*iv*) the relative importance of the attributes in the respective index, which is expressed by means of normalized priority vectors. The value of each of these indexes is finally obtained as a result of a fuzzy inference procedure, which is a *crisp* value ranging from 0 to 1. This procedure allows us to express the values taken by the indicators in a particular agroecosystem by means of both *crisp* values and fuzzy numbers, the latter being frequently a more rigorous and realistic way of representing the estimations of the soil properties in any emplacement. Verification tests show the satisfactory response capability of the index to changes in the soil properties. The use of the designed *S-DQI* for routine monitoring of the quality of farming soil allows the estimation of the changes induced in the soil due to use, which is helpful to assess systematically the sustainability of the agricultural practices.

1. Introduction

Fuzzy logic and fuzzy sets theory are being increasingly used in the environmental field, since they are the appropriate mathematical tools to deal with the uncertainty and imprecision (Klir and Yuan, 1995) which are frequently inherent to the nature of many data handled in environmental studies (Chowdhury, 2012; Darbra et al., 2008; Dong et al., 2014). Thus, fuzzy approaches – procedures based on fuzzy logic – have been successfully used in the assessment of health and environmental risks associated with the management of both water (Cabanillas et al., 2012; Deng et al., 2012) and solid waste (Srivastava and Nema, 2011), as well as in the management of air quality (Ping et al., 2010; Zhang and Huang, 2011). Several fuzzy models have also been applied to the assessment of sustainability (Liu et al., 2012; Pislaru et al., 2008) and to environmental impact assessments (Biswas et al., 2011;

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Duarte et al., 2007), for which new methodologies based on fuzzy logic have been developed in recent years (Peche and Rodríguez, 2009, 2011). Fuzzy logic is also especially useful in the assessment of air quality (Assimakopoulos et al., 2013; Carbajal-Hernandez et al., 2012) and water quality (Gharibi et al., 2012; Rahimi and Mokarram, 2012), although its application to soil quality assessment is still rather scarce (Torbert et al., 2008; Xue et al., 2010, 2011). Fuzzy logic has also been successfully used in combination with genetic algorithms (GA) and Geographical Information Systems (GIS) to carry out environmental assessments, such as aquatic habitat suitability (Fukuda et al., 2011) and diverse soil characteristics (Giordano and Liersch, 2012; Liu et al., 2013). The most common assessment of environmental quality is carried out by means of quality indexes (*QI*). The use of quality indexes is a widespread practice, in particular, in the assessment of soil quality (Andrews et al., 2002; Rahmanipour et al., 2014). This is conditioned, among other factors, by the functionality of the soil under assessment and by its geophysical and morphological characteristics. However, soil heterogeneity, seasonal variation of some of its physicochemical and biological characteristics and, ultimately, the inherent complexity of soil make it difficult to rigorously assess its quality or suitability for a particular function by means of a universal conventional index, which can be systematically used for that purpose (Qui et al., 2009). For these reasons, it is necessary to design specific indexes to assess soil quality in terms of the soil functionality, which can also be adapted – if necessary – to the characteristics of the region in which it is located (Andrews et al., 2004; Imaz et al., 2010). In general, the design procedures of soil quality indexes (*SQI*) are based on: (*i*) identifying the minimum set of indicators of the physicochemical and biological properties which determine the soil quality for a given function, (*ii*) estimating subsequently the relative importance of these properties as a measure of its contribution to the soil quality under consideration, and (*iii*) grouping all the indicators into a single index of soil quality, for which their relative importance is taken into consideration (Askari and Holden, 2014; Rodrigues de Lima et al., 2008). The most recently applied methodologies for the assessment of soil quality by means of an index consist of the selection of a Minimum Data Set (MDS) of sensitive physical, chemical and biological indicators by Principal Component Analysis (PCA), the subsequent application of diverse weighting methods to measure the importance of these indicators, and the ultimate development of a quality index by means of linear or non-linear score functions (Chen et al., 2013; Rahmanipour et al., 2014; Swanepoel et al., 2014; Tesfahunegn, 2014). However, the imprecision and inaccuracy inherent to many parameters and variables included in the quality indexes, and the subjectivity of the estimation of the contribution of these parameters to the *SQI* suggest that the use of fuzzy approaches should enable more rigorous and realistic estimations of soil quality to be carried out (Arunraj and Maiti, 2009; Gentile et al., 2003; Khan et al., 2002, 2004; Li et al., 2008). Moreover, the recent development of new procedures based on fuzzy logic for the design of environmental quality indexes opens new ways for assessing the soil quality (Peche and Rodríguez, 2012).

In line with these considerations, the aim of this work is to design an index based on fuzzy logic, which is addressed to assess the dynamic quality of agricultural soils – *Soil Dynamic Quality Index* (*S-DQI*). The use of this *S-DQI* for routine monitoring of the dynamic quality of soil in agricultural farms allows the changes induced in the soil due to its use to be estimated, which is helpful to assess the sustainability of the agricultural practices, and therefore to prevent soil degradation.

The dynamic quality of agricultural soils is determined by the values which are taken by certain physical, chemical and biological properties, which efficiently and effectively monitor critical soil functions for farming (Karlen et al., 2003). For this reason, this *S-DQI* is described by a group of three indexes ($S\text{-}DQI_{PHYS}$, $S\text{-}DQI_{CHEM}$, $S\text{-}DQI_{BIOL}$), each one designed to evaluate the dynamic quality of the agricultural soil with respect to their physical, chemical and biological characteristics, respectively. In order to check the response capability of the *S-DQI* as a diagnostic tool for the measurement of the dynamic quality of agricultural soils, it is used to verify the dynamic quality of some soils which had been previously categorized by the panel according to their physicochemical and biological characteristics.

2. Design of the Dynamic Quality Index for agricultural soils

Each index of the group ($S\text{-}DQI_{PHYS}$, $S\text{-}DQI_{CHEM}$, $S\text{-}DQI_{BIOL}$) is designed from the opinion of a panel of experts by means of a previously developed versatile and rigorous methodology based on fuzzy logic, which enables the design of specific indexes for the assessment of the quality in any environmental compartment (Peche and Rodríguez, 2012). The design procedure requires: (a) the selection of the physical ($a_{i\text{-}PHYS}$), chemical ($a_{i\text{-}CHEM}$) and biological ($a_{i\text{-}BIOL}$) attributes or properties of the soil which determine its dynamic quality for farming, and the indicator for quantifying each of them – ($I_{i\text{-}PHYS}$), ($I_{i\text{-}CHEM}$) and ($I_{i\text{-}BIOL}$), respectively; (b) the estimation of the beneficial contributions of the attributes to the corresponding index by means of fuzzy sets, which are described by its membership functions $\bar{\mu}_{\bar{B}_i}(S_{i\text{-}PHYS})$, $\bar{\mu}_{\bar{B}_i}(S_{i\text{-}CHEM})$ and $\bar{\mu}_{\bar{B}_i}(S_{i\text{-}BIOL})$; and (c) the estimation of the relative importance of the attributes in their respective index by means of the Analytical Hierarchical method (AHM) (Saaty, 2008), which is expressed by the normalized priority vectors W'_{PHYS}, W'_{CHEM} and W'_{BIOL}. Finally, the value of each of these indexes is obtained as a result of a fuzzy inference procedure (Takagi and Sugeno, 1985), which is a *crisp* value ranging from 0 to 1. The different stages of the design procedure of the indexes $S\text{-}DQI_{PHYS}$, $S\text{-}DQI_{CHEM}$, $S\text{-}DQI_{BIOL}$ are described in detail below. A diagram is included at the end of this section in order to provide a comprehensive overview of the index design procedure.

2.1. The panel

The design of the index was carried out by a panel, which was coordinated by two experts in the management of environmental information, as well as in the use of fuzzy logic, fuzzy sets theory and the mathematical treatments required for the design of the index. The research groups of different university departments and technology centers of the Basque Country were contacted in order to organize the panel, whose area of expertise was in the study and management of soil. They were informed about the characteristics of the *S-DQI*, the design methodology and the tasks and estimations they would be asked to do in the procedure. In order to consider the different aspects related to the quality of agricultural soils, it was agreed to include eight panelists, among them, eco-microbiologists, eco-biologists, vegetal biologists, chemists, environmentalists and environmental technologists. Each group decided which of their members would take part as panelists, in accordance to their expertise and to the required composition of the panel. The general working method of the panel at the different stages of the procedure was as follows: (a) A meeting was held during which the panel was informed by the coordinators about the work to be done at each stage. The coordinators provided them with the necessary material – questionnaires, matrixes, graphs, . . . –, which was specifically designed to get the required information, estimations and/or assessments, and gave them the instructions to use it. (b) Each panelist did his or her work according to his or her criteria, in collaboration with their respective research groups – if necessary –, and sent it to the coordinators. (c) The coordinators organized and analyzed the information and/or the estimations sent by the