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AGRO-ECOLOGICAL SOIL EVALUATION FOR MONITORING WATER QUALITY USING MICROLEIS DSS

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Abstract

Soil degradation has both indirect and direct effects on the quality of surface and ground waters. In this sense, agriculture is one of the key activities causing water quality degradation in many parts of Mediterranean systems. In the European Union, the purpose of the Water Framework Directive (European Commission, 2000) is to establish a framework for the protection of inland surface, transitional, coastal and ground waters too. A major source of surface and ground water pollution is the diffuse contamination caused by nitrates in agricultural lands. This specific water protection was regulated by the Nitrates Directive (ND, 1991/676/EC), which in Spain was developed by a Royal Decree (261/1996/BOE), and in Andalusia region by a Decree (36/2008/BOJA) for the designation of water quality vulnerability zones (22 zones) and an Order of the Regional Government of Andalusia (18.11.2008/BOJA) to establish the action programs (1 unique program) to be implemented by farmers. However, the Nitrates Directive considers that different action programs may be established for different vulnerable zones or parts of those areas. Also, these action programs must take into account scientific and technical information that are available on each particular soil and climatic conditions, such as rainfall erosivity, length of the growing season, slope, soil infiltration and soil denitrification capacity. Within this context, the agro-ecological decision support system MicroLEIS DSS (technology developed by CSIC-IRNAS and transferred to Evenor-Tech, www.evenor-tech.com) is considered a very appropriate tool to include the soil and climatic attributes for a better identification of vulnerable zones and formulation of action programs. In this paper, the MicroLEIS DSS modelling infrastructure to predict soil erosion and contamination risks (ImpelERO and Pantanal models, basically) is discussed, as a scientific approach to identify detailed vulnerable areas, and formulate site-specific management plans for sustainable water use and protection in Andalusia region. The high variability of the results from this agro-ecological land evaluation research in Water Quality Vulnerability Zones demonstrates the importance of using soil information in decision-making regarding the formulation of site-specific soil use and management strategies.

Keywords: Andalusia, decision support system, GIS-based model, expert system, MicroLEIS, soil quality, Water Framework Directive.

1. INTRODUCTIÓN

Soil quality is essential not only for increased productivity, but also for the agro-ecosystem to provide its services and benefits derived from the regulation of ecosystem processes (Carpenter, 2002; De Groot et al., 2002; Wani et al., 2005). Following Karlen et al., (1997) the main ecosystem services provided by soil systems are:

- Sustaining biological activity, diversity, and productivity;

- Regulating and partitioning water and solute flow;

- Filtering, buffering, degrading, immobilizing, and detoxifying organic and inorganic materials, including industrial and municipal by-products and atmospheric deposition;

- Storing and cycling nutrients and other elements within the earth's biosphere; and

- Providing support of socioeconomic structures and protection for archeological treasures associated with human habitation.

Taking this into account, soil degradation has both indirect and direct effects on the quality of surface and ground waters. In this sense, agriculture is one of the key activities causing water quality degradation in many parts of Mediterranean systems. In countries around the Mediterranean basin, the degradation of soil and water resources is a serious threat for human welfare and the natural environment as a result of the climate, topography, soil characteristics, and peculiarities of agriculture management. The detrimental effects of agricultural practices on soil quality include erosion, loss of organic matter, desertification, salinization, compaction, landslide, pollution, etc. The resultant impacts on water resources include pollution due to nutrient and pesticide (Brainwood et al., 2004), increase of water temperature (Nelson and Palmer, 2007), modification in-stream biogeochemical of processes that drive oxygen, nutrient, and sediment cycling (Baker, 2003), and others degradation aspects affecting water quality and quantity. It is clear the reason of soil management proper which should be considered as another tool in the regulatory and land use tool-box to support water quality.

The water quality is affected by both macro- and micro-scale factors. Macro-scale factors include climate, landscape and parent material of the area, while micro-scale factors include land use and management at field or farm level (Brainwood et al., 2004). Previous studies revealed that there is a strong relationship between land use and quality of water bodies (Meybeck, 2002; Tong and Chen, 2002; Hanrahan et al., 2003; Simeonov et al., 2003; Ahearn et al., 2005; Crosa et al., 2006; Stubblefield et al., 2007). This means that changes in land use and management practices can have considerable impact on water quality parameters.

With the increased public concerns about water quality degradation, different EU policies such as Water Framework Directive and also Nitrate Directive are contributing to water protection. The Water Framework Directive establishes a legal framework to protect and restore clean water across Europe and ensure its long-term sustainable use. In addition, the Nitrates Directive forms integral part of the Water Framework Directive where it is one of the key instruments in the protection of waters against agricultural pressures. The various steps of implementation of the Directive are:

- Identification of polluted or threatened waters (N).

- Designation of "vulnerable zones" (NVZs)

- Establishment of Code(s) for good agricultural practice, to be implemented by farmers on a voluntary basis.

- Establishment of Action Programs, to be implemented by farmers within NVZs.

- National monitoring and reporting every four years.

Monitoring is the main tool used by Member States to classify the status of each water body where it is a section of a river or other surface water or a distinct volume of groundwater. The directive sets a common approach for monitoring water quality across all Member States but does not specify the supplied methods. It is up to Member States to decide the best method based on local conditions and existing national approaches. In Spain was developed by a Royal Decree (261/1996/BOE), and in Andalusia region by a Decree (36/2008/BOJA) for the designation of water quality vulnerability zones (22 zones) and an Order (18.11.2008/BOJA) to establish the action programs (1 unique program) to be implemented by farmers. However, the Nitrates Directive considers that different action programs may be established for different vulnerable zones or parts of those areas. Also, these action programs must take into account scientific and technical information that are available on each particular soil and climatic conditions, such as rainfall erosivity, growth season length, slope gradient, soil infiltration rate and soil denitrification capacity.

In this sense, emerging technologies in data and knowledge engineering provides excellent possibilities in monitoring water quality regarding on land evaluation processes. The application phase of land evaluation systems is a process of scaling-up from the representative areas of the development phase to implementation in unknown scenarios. The application phase - previously accomplished manually - can now be executed with computer-assisted procedures. This involves the development and linkage of integrated databases, computer programs, and spatialization tools, constituting decision support systems (De la Rosa and Van Diepen, 2002).

Decision support systems are computerized technology that can be used to support complex decision-making and problem-solving (Shim et al., 2002). Opinions are wide-ranging as to what constitutes a decision support system. A database management system could arguably be used as a decision support system for certain applications. Many people consider geographic information systems very useful decision support systems (Booty et al., 2001). Classic decision support system design comprises of components for i) sophisticated database management capabilities with access to internal and external data, information, and knowledge, ii) powerful modeling functions accessed by a model management system, and iii) simple user interface designs that enable interactive queries, reporting, and graphing functions (Shim et al., 2002).

In this paper, the approaches used and experience gained in to develop the agro-ecological decision support system for soil use and protection, called MicroLEIS DSS are discussed for monitoring water quality. The main objective of this paper is to point out the possibilities to segregate homogeny subzones within the already defined Water Quality Vulnerability Zones in Andalusia (Order 18.11.2008/BOJA), by application of the agro-ecological decision support system MicroLEIS DSS. Also, different aspects of land use and management referred to each vulnerability subzones are discussed. In this way 5 agro-ecological land evaluation models (Raizal, Arenal, Pantanal, Almagra and ImpelERO (De la Rosa et al., 2004)) constituents of this DSS software were selected in order to make strategies related to land evaluation at a regional level, such as identification of vulnerability subzones, restoration of marginal areas, and diversification of crop rotation. Results obtained from each evaluation models are presented and discussed in this research work. In summary, MicroLEIS Technology appears to be a useful tool for monitoring specific action programs for water protection based on soil data survey and related variables. Additionally, this kind of assessment can be extrapolated to other parts of Europe.

2. STUDY AREA DESCRIPTION

On the basis of the semi-detailed natural resources surveys of Sevilla and Cordoba provinces, 5 subzones were selected within the Water Quality Vulnerability Zone 2: Guadalquivir Valley (Figure 1) established by the Order 18.11.2008/BOJA. A general description of each subzone is summarized in Table 1. The geographic coordinates of the study area is 36º 42´ to 37º 57´ north latitude and 4º 17´ to 6º 26´ west longitude approximately. Its slopes range from < 2 to 30%, and the elevation is from 2 to 740 m above sea level. For each subzone, the representative meteorological station was selected based on monthly mean climate variables for the long term during 1961 till 1990. The identification of the 5 subzones was based on soil distribution, because they occupy large proportions on each subzone. The morphological and analytical properties of the typical soil profiles were taken from the soil profile database of SEISnet (www.evenor-tech.com).

3. MICROLEIS AGRO-ECOLOGICAL DECISION SUPPORT SYSTEM

The agro-ecological decision support system, MicroLEIS DSS (De la Rosa et al., 2004; 2009), through its 12 land evaluation models, analyses the influence of selected soil indicators on critical soil functions referred to: 1) land productivity (agricultural and forest soil suitability, crop growth, and natural fertility), and 2) land degradation (runoff and leaching potential, erosion resistance, subsoil compaction, workability, and pollutant absorption and mobility) (Figure 2). These empirical-based models were basically developed as sophisticated tools based on artificial intelligence techniques, using soil information and knowledge of the Mediterranean region. Input variables are physical/chemical soil parameters (e.g. useful depth, stoniness, texture, water retention, reaction, carbonate content, salinity, or cation exchange capacity) collected in standard soil surveys, monthly agro-climatic parameters for long-term period, and agricultural crop and management characteristics. Since the late 1980s, MicroLEIS DSS has evolved significantly towards a user-friendly agro-ecological decision support system for environmentally sustainable soil use and management. The design philosophy is a toolkit approach, integrating many software instruments: databases, statistics, expert systems, neural networks, Web and GIS applications, and other information technologies. Input data warehousing, land evaluation modelling, model application software and output result presentation are the main development modules of this system.

MicroLEIS DSS has proved to be an appropriate methodology for converting knowledge on land use and management systems, as estimated by research scientists, into information that is readily comprehensible to policy makers and farmers, on Mediterranean soils and it is now applied and tested in other countries such as Iran or Argentina. Its land evaluation models allow a site-specific application, providing an effective tool for assessing the suitable land use and management at a local scale. All the information needed to select the suitable land use and management can be entered separately, hence it is possible to establish the exact soil, climate, and farming conditions.

Presently, a spin-off from the CSIC (named Evenor-Tech; www.evenor-tech.com) has been launched as a platform for the development and diffusion of the MicroLEIS technology. Also, a reduced CD-ROM version of MicroLEIS DSS is included into the book "Evaluación Agro-ecologica de Suelos para un Desarrollo Rural Sostenible" (De la Rosa, 2008).

4. VULNERABILITY ZONES

4.1. Water and wind erosion

Results of applying Raizal (soil erosion risk) model in the 5 vulnerability subzones indicate the vulnerability classes and soil erosion loss for each site (Table 2). The highest risks are obtained for the traditional olive crop, with the Campina subzone (SZ22: Typic Chromoxerert) presenting the highest sensitivity, with a soil loss very close to 10 t/ha/year.

This identifying of vulnerable area for soil degradation is helpful to improve knowledge about the extent of the areas affected and, ultimately, to develop measures to control the problem soils. For example, because of the very slow rate of soil formation, any soil loss equal or more than 1 t/ha/year can be considered irreversible within a time span of 50-100 years. Losses of 20 to 40 t/ha in individual storms, which may occur once every two or three years, are measured regularly in Mediterranean areas, and in extreme events, there can be a loss of more than 100 t/ha (Morgan, 1992).

4.2. Contaminants risk

The probability of agro-chemical diffuse contamination, by application of the Arenal and Pantanal (general and specific soil contamination risk) models, for the respective target crops (annual crops and fruit plantations) in the 5 vulnerability subzones (Table 3). In order to rationalize the agro-chemical application, the lowest vulnerability (V1) for most of contaminants (N and P fertilizers, heavy metals, and pesticides) is predicted for soils that have low runoff and infiltration rate which are rich in clay and carbonate content, such as SZ22 (Typic Chromoxerert) and SZ23 (Salorthidic Fluvaquent). Independently of the nutrient needs for crop yield, the application of fertilizers is considered that usually exceeds the functional capacity of the soil to retain and transform such nutrients. In many cases, the saturation of the soil with nitrogen and phosphate has led to losses of nitrates into shallow groundwater and saturation of the soil with phosphate, which may also move into the groundwater (Zalidis et al., 2002).

The maximum specific risk from the extensive use of pesticides is due to the leaching and drainage of pesticides into the surface- and groundwater. Several soil functions can be degraded, including the food web support, the retention and transformation of toxicants and nutrients, and soil resilience. Today, the frequent use of herbicides is drastically changing the methods of crop production, but their impacts on soil quality/degradation are still not known exactly. Chemical weed control is identified as an important limiting factor in the adoption of the no-tillage system. In this case, the risk of soil contamination by herbicides must be analyzed because, ironically, farming practices to remedy eroded soils can increase soil degradation by contamination.

5. AGRICULTURAL MANAGEMENT PROGRAM.

In order to define site-specific strategies of sustainable agriculture, soil management analysis must be a second phase after land use planning. It is obvious that the increasing use of mechanized cultivation has led to a substantial increase in rates of soil degradation. However, agricultural intensification is not necessarily or directly related to soil degradation. For example, soil degradation in an intensive farming system using soil protection practices may be lower than in a more extensive system that does not apply them. In Mediterranean areas, it is clear that water erosion is one of the major soil degradation processes. To reduce the soil erosion risk and related soil degradation processes, the soil management practices must be formulated for each particular site.

For crop diversification, results of applying the Almagra (agricultural soil suitability) model in the 5 vulnerability subzones previously classified as agricultural lands are shown in Table 4. For this qualitative model, matching tables following the principle of maximum limitation for soil factors are used to express soil suitability classes for 12 Mediterranean crops. The Vega subzone (SZ25: Typic Xerofluvent) has nearly ideal physical and chemical soil properties for most crops, but less for perennial ones, especially for olives. On the other hand, soils from Terrazas subzone (SZ24: Aquic Haploxeralf) offer lower aptitude for most of the crops, due to its deficient drainage conditions mainly. Generally, the excessive content of carbonates in soils is the limiting factor which more appears at the evaluation. Wheat (Triticum aestivum), soybean (Glycine max), sunflower (Helianthus annus), sugarbeet (Beta vulgaris) and alfalfa (Medicago sativa) are the most-suitable crops for most of the site.

For organic matter restoration, the recommended crop residues treatment for various testing crops in the 5 vulnerability subzones, by application of the ImpelERO (erosion/impact/mitigation) model are shown in Table 5. The most-repeated option for each crop and land area is to bury in the soil the maximized crop residue; being collected or burned options considered only in rare cases. These soil evaluation results try to avoid the negative consequences of tillage practices that strongly accelerate soil erosion processes by destroying soil organic matter and soil structure. Loveland et al. (2000) recorded a decrease in mean soil organic carbon from arable ley sites of 0.49% over a 15-year period. Increasing the soil organic matter levels is critical for sustainable agriculture. The best way to increase the stable soil organic matter is to improve crop yields that maximize crop residues for incorporation into the soil. In general terms, it has been estimated that an annual return of 5 t/ha of crop residues could keep soils in equilibrium with present levels of soil organic matter. However, the efficiency of conversion of that carbon to stable soil organic matter is not constant, and depends on several variables. On the other hand Merino et al., (2004), shows that changes in soil properties as a consequence of the transformation of cropfield to intensive grassland do not imply substantial changes in soil organic matter. On the contrary, afforestation resulted in increases in soil organic matter content.

For tillage intensity, the recommended management practices from application of the ImpelERO (erosion/impact/mitigation) model for various tested crops in the 5 vulnerability subzones are summarized in Table 5. The soil tillage practices are formulated for each specific site in relation to the tillage direction, operation sequence, and roughness produced, as a set of concrete measures against water erosion. The implement types used for each operation sequence are also recommended by ImpelERO model. At the Vega (SZ25: Typic Xerofluvent) and Marismas (SZ23: Salorthicic Fluvaquent) subzones, tillage direction is irrelevant due to the low slope of these soils. Also, tillage direction is taking into account at the others sites due to sediment transport is much more rapid with plowing up and down the slope than it is along the contour. Moreover, contour tillage can move material either up and down, depending on the direction in which the tillage turns the soil: contour tillage in which the soil is turned uphill moves rather less material.

According to the physical and chemical properties of the dominant scattered soil (Typic Chromoxerert) in the Campiña (SZ22), the number of tillage operations can be greatly reduced for the wheat crop. This soil tillage intensity can range from full-width maximum tillage to zero tillage (i.e. intensive tillage, reduced tillage, plowless tillage, minimum tillage, and no-tillage). The most common highly intensive tillage system of dry farming consists of: moldboard plowing to break the hardened soil surface, and much surface disking and harrowing to reduce soil clod size and to control weeds. This repeated tillage system accelerates decomposition of organic matter, thus affecting soil physical, chemical, and biological attributes of soil quality. It is clearly inappropriate for most soils, and must be avoided if soil erosion is to be combated. On the contrary, in the no-tillage system the soil is left undisturbed, and includes: direct sowing, and weed control with herbicides. Several studies show a continuous increase in organic matter and improvement in soil structure, restoring and improving soil quality, and that crop yields increase, and soil erosion is controlled.

With regard to the micro-topography or random roughness (Table 5) of the soil surface produced by tillage, conventional implements (e.g. plow moldboard) that cause soil inversion are particularly appropriate for slope soils, due to the high surface roughness (> 30 mm). Increasing the surface roughness decreases the transport capacity and runoff detachment by reducing the flow velocity. During a rainfall event, rough surfaces are eroded at lower rates than are smooth surfaces under similar conditions.

6. CONCLUSION REMARKS

The MicroLEIS DSS, combining biophysical land evaluation models that were previously peer reviewed and validated, appears to be a good example of advisory/ decision-support tools in the direction of exploiting and disseminating the scientific data and knowledge on monitoring water quality and proposing specific action programs. This DSS can be especially useful in prevention of soil and water degradation based on the within-region variability of soils and climate conditions.

The high variability of the results from this agro-ecological land evaluation research in Water Quality Vulnerability Zones demonstrates the importance of using soil information in decision-making regarding the formulation of site-specific soil use and management strategies. Soil erosion and contamination risks, such as predicted by Raizal and Pantanal models of the MicroLEIS DSS, result to be good indicators to propose specific action programs for each subzone within the Vulnerability Zone 2: Guadalquivir Valley.

Agricultural land use systems are well formulated from the Almagra land suitability model of the MicroLEIS DSS. Vulnerability subzone with Typic Xerofluvent soils allows the maximum diversification of crop rotation and optimum crop production. Within these agricultural lands, vulnerability areas for soil erosion are specially related to Typic Chromoxerert soils.

The proposed agricultural soil management programs follow the general trend for environmentally sustainable agriculture: i) increase the level of soil organic matter by maximizing crop residues; ii) follow the contour for tillage direction; iii) reduce tillage intensity; iv) diversify tillage implements; v) consider optimum soil workability; vi) avoid subsoil compaction; and vii) reduce chemical weed control. However by using the ImpelERO model of the MicroLEIS DSS, detailed and specific soil management systems are proposed for each particular subzone, showing the management characteristics: tillage intensity, workability timing and machinery type, the maximum variability. Vulnerability subzones with Typic Chromoxeret soils are the most sensitive lands for the different management practices analyzed.

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Maria Anaya-Romero

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