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Francaviglia R., Marchetti A., Mecella G., Scandella P.

in

Zdruli P. (ed.), Steduto P. (ed.), Kapur S. (ed.).
7. International meeting on Soils with Mediterranean Type of Climate (selected papers)

Bari : CIHEAM
Options Méditerranéennes : Série A. Séminaires Méditerranéens; n. 50

2002
pages 313-322

LAND USE PLANNING. A GIS APPLICATION TO ASSESS SOIL QUALITY FOR AGRICULTURAL MANAGEMENT PURPOSES

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Introduction

Soil fragility evaluation and the assessment of the impact of human activities on a given territory are the basis in every type of land planning. Moreover, public Authorities must be provided with operative tools addressed to the protection of the environment in general, and of agricultural areas in particular, which should be effective and user friendly also from the informatic point of view. The classification of the agricultural areas according to their different levels of fragility and aptitude to productivity must be necessarily based on the soil analytical survey and description, including physico-chemical properties, morphology, hydrogeological characteristics, the actual and the potential land use.

A Geographical Information System (GIS) provided with a proper set of data-bases of the area, and containing the related information made available from the Public Institutions and the Research (soil, water, air, flora, fauna, urban and industrial settlements, landscape, cultural heritage, socio-economic condition, etc.), is the only effective operative tool (Bertozzi *et al.*, 1999). The next step is the assessment of the actual state of the resources and their risk of degradation, in order to plan the measures able to prevent or at least to limit any negative effect that could arise from the different land uses.

This paper represents a model applied to a large agricultural area, based on common software tools and able to provide a quick evaluation of its fragility, through the use of proper indicators, and the planning of different management strategies. The contribution is an example of pilot study to be applied at a wider scale, in consideration of the amount of pedological information available in the country, thus providing the users with a reference tool, very effective in different applications in the agri-environmental sector.

Materials and methods

The area is located in Central Italy (Umbria Region), and represents the watershed of the Upper Tiber Valley. The climate is typically Mediterranean, physiography and geomorphology are rather varied, soils derive from sandstone, alluvial and limestone substrata, and agriculture is intensive and specialised (corn and tobacco in single-crop systems).

The system has been applied to an area of about 25,000 hectares (UAA equal to 17,000 hectares), where the data-bases of soils with the derived cartography, climate and crops were available from previous researches (Tombesi *et al.*, 1978-79; Mecella *et al.*, 1985-86).

The amount of information related to morphology, physico-chemical and hydrological parameters (about 360 soil samples, see Figure 1) has allowed a high detail of investigation as required for land use planning purposes (1:25,000).

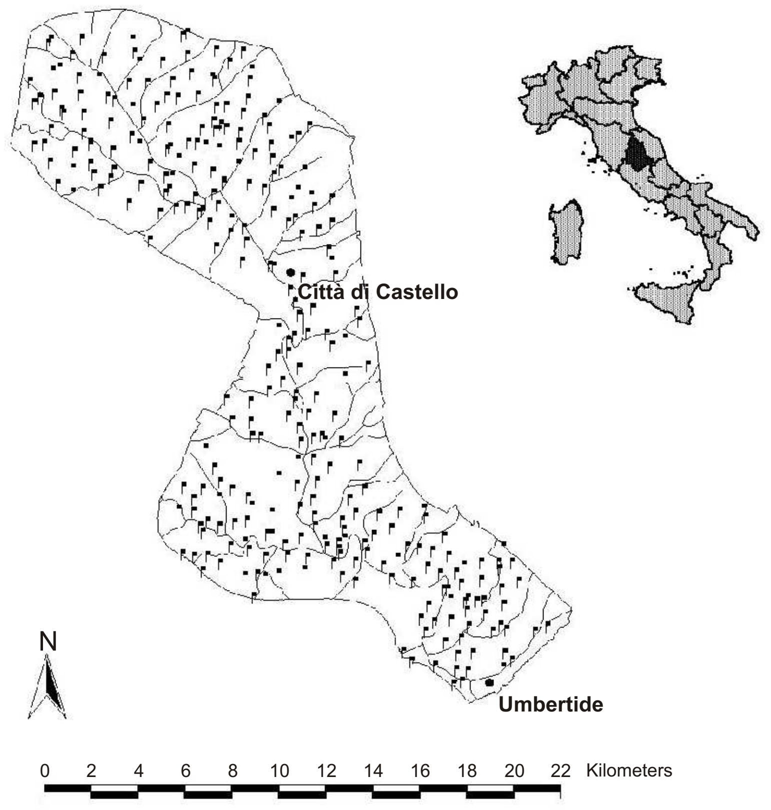

Figure 1. Location of soil samples.

The following parameters of the surface soil layer have been considered: pH, Cation Exchange Capacity (CEC), Ca/Mg ratio, texture, permeability, and available water content. The evaluation criteria are reported in Table 1. Moreover, organic matter content has been evaluated considering three classes of texture (sandy, loamy and clayey soils) and four levels of organic matter (Table 2).

Finally, the indicator of soil global fertility has been elaborated. This is a complex indicator based on two submodels. The first considers soil chemical fertility, i.e. pH, available P_2O_5 and exchangeable K_2O levels in relation to three macro-classes of soil texture. Since sandy soils in theory contain lower amounts of nutrients in comparison with loamy and clayey soils, a lower threshold of sufficiency has been attributed to them. The same assumption has been applied to loamy soils in comparison with clayey soils. The distinction based on soil pH assumes that:

- the worst case is for soils with pH < 5.0 or > 8.5;
- the intermediate case is for pH in the range 5.1-6.5 or 7.9-8.4;
- the optimal case is that of pH in the range 6.6-7.8.

The resulting classes of chemical fertility are reported in Table 3.

The second submodel takes into account soil intrinsic fertility, and considers the level of organic matter in relation to the yearly coefficient of mineralisation (a function of organic matter, clay and total limestone content).

This submodel evaluates the number of years N required for the complete mineralisation of soil organic matter, according to the equation:

$$N = \frac{OM}{K_2}$$

with the annual coefficient of mineralisation K_2 (Rémy and Marin-Laflèche, 1974) given by:

$$K_2 = 1200 \cdot (C + 20)^{-1} \cdot (CaCO_3 + 20)^{-1}$$

Where: OM = % organic matter, C = % clay, $CaCO_3$ = % total limestone.

Soil intrinsic fertility is classified as shown in Table 4. Soil global fertility is defined according to a matrix that considers chemical and intrinsic fertility (Table 5).

During data processing, soil profiles parameters have been normalised to 40 cm to build up a virtual horizon with a prefixed depth. ArcView 3.2 was used for the georeferentiation of the soil samples and the realisation of the maps. The maps have been elaborated with the ArcView extension Spatial Analyst and the IDW (Inverse Distance Weighted) interpolator.[1] The use of this method assumes that the variable being mapped decreases in influence with distance from its sampled location.

The elaboration of the parameters and the indicators have been the basis for a set of thematic maps, which allowed the evaluation of soil sensitivity. The realisation of these maps is a first approach to represent a preliminary set of soil quality indicators, as a consequence of the collaboration between the Institute and the National Topic Centre "Soils and Contaminated Sites" of the National Agency for the Protection of the Environment (ANPA, 2000).

Results and Discussions

Through the GIS application different maps have been derived (Fig. 2-8): pH, Cation Exchange Capacity, Ca/Mg ratio, Soil Texture according to the USDA classification, Permeability, Available Water Content, and Soil Organic Matter in relation to soil texture (to assess the structural stability of soils). Among the others, Soil Global Fertility (Fig. 9) summarises the many chemical, physical and hydrological information, whose parameterisation requires the knowledge of specific personnel well trained in pedology, agronomy, chemistry, etc. Moreover, the synthesis cartography would provide the responsible of land planning with an easy operative tool at territorial level, to organise the use and the management of agricultural areas at different aptitude to productivity.

[1]Data have been processed at the AMB-GSI sector of ANPA, with the collaboration of Dr. M. Marinelli.

In particular, the following considerations can be derived:

- about 80 % of the area has a *soil reaction* slightly alkaline (7.4-7.8);
- *cation exchange capacity* is medium (10-20 cmol kg^{-1}) in approximately 90 % of the area;
- about 48 % and 43 % of the area, has an optimal value of the *Ca/Mg* ratio (4-8) and an Mg deficiency (>8) respectively;
- *soil texture* is mainly sandy-loam (40 % of the area) and loam (52 %);
- *permeability* is moderately slow (5-20 mm h^{-1}) in 75 % of the area, and slow (1-5 mm h^{-1}) in about 23 % of the area;
- approximately 95 % of the area has an *available water content* in the range 40-60 mm, referred to a 40 cm layer;
- *soil organic matter* content is very low and low in 18 % and 52 % of the area, respectively; 28 % has a medium content;
- *soil global fertility* is mainly medium (70 % of the area), low and very low (10 %) and moderately high (17 %).

The fast elaboration that is a consequence of the informatic process, and the high level of detail arising from the plenty of information, have allowed the selection of the thematic maps more effective to assess the problems emerging in the area that are essential for agricultural planning. In fact, results show that organic matter content and soil global fertility status are not at the optimum value, mainly in the southern part of the watershed, and this is a common feature in soils under a Mediterranean type of climate mainly as a result of intensive cultivation based on chemical fertilisers.

A notable remark can be made for permeability, since this parameter is used in different soil interpretations, such as suitability for irrigation and drainage systems, and is often negatively affected from agricultural practices leading to soil compaction. Soils with low permeability values are predominant in the area, and this can pose a problem during the distribution of irrigation. In other words, if the intensity of water distribution should exceed soil permeability, some problems could derive from an excess of moisture in the root zone. These anoxic conditions can be favoured also by the prevalence of fine sand over coarse sand (the mean value of the ratio is 5.8), which has a negative effect on soil structural stability that, in turn, decreases the permeability. And in relation to tillage operations leading to soil compaction, it would be effective to assess the maximum physical loading of a soil which will not produce increases in bulk density, or decreasing of permeability.

Table 1. Soil parameters evaluation.

pH	
6.1 - 6.5	Slightly acid
6.6 - 7.3	Neutral
7.4 - 7.8	Slightly alkaline
7.9 - 8.4	Moderately alkaline
8.5 - 9.0	Strongly alkaline
CEC cmol kg^{-1}	
5 - 10	Low
10 - 20	Medium
20 - 40	High
Ca/Mg	
< 4	Mg excess
4 - 8	Optimal equilibrium
> 8	Mg deficiency
Permeability mm h^{-1}	
1 - 5	Low
5 - 20	Moderately slow
20 - 60	Medium (optimal)

Table 2. Soil organic matter evaluation* and soil texture triangle.

USDA texture classes			
S.O.M. level	Sands Loamy-Sands Sandy-Loams	Loams Sandy-Clay-Loams Silty-Loams Sandy-Clays Silts	Clays Clay-Loams Silty-Clays Silty-Clay-Loams
Soil Organic Matter %			
Very low	< 0,8	< 1,0	< 1,2
Low	0,8 - 1,4	1,0 - 1,8	1,2 - 2,2
Medium	1,5 - 2,0	1,9 - 2,5	2,3 - 3,0
High	> 2,0	> 2,5	> 3,0

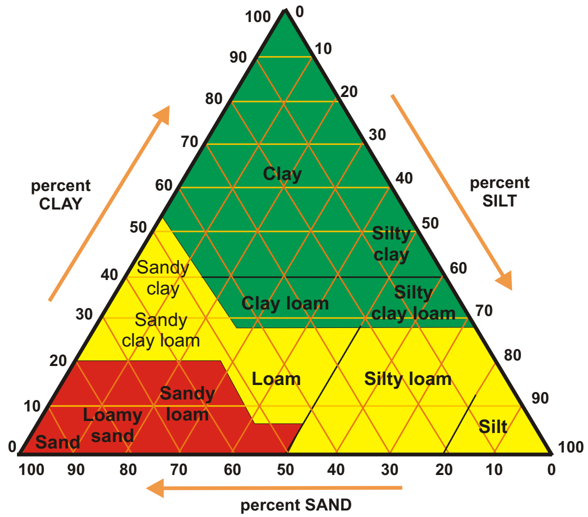

Table 3. Classes of soil chemical fertility.*

Texture	K_2O ppm	< 80			80-100			100-120			120-160			>160		
	pH / P_2O_5 ppm	<5.0 >8.5	5.1-6.5 7.9-8.4	6.6-7.8	<5.0 >8.5	5.1-6.5 7.9-8.4	6.6-7.8	<5.0 >8.5	5.1-6.5 7.9-8.4	6.6-7.8	<5.0 >8.5	5.1-6.5 7.9-8.4	6.6-7.8	<5.0 >8.5	5.1-6.5 7.9-8.4	6.6-7.8
Sands S > 60 %	<23	5	5	4	5	4	4	4	3	3	4	3	3	4	3	3
	23-30	4	4	3	4	3	3	4	3	2	3	2	2	3	2	1
	31-34	4	3	3	3	2	2	3	2	1	3	2	1	3	2	1
	>34	3	3	3	3	2	2	3	2	2	3	2	2	2	2	2
Loams	<30	5	5	5	5	5	5	5	4	4	4	3	3	4	3	3
	30-39	5	4	4	5	4	4	4	3	3	4	3	2	3	2	1
	39-48	4	3	3	4	3	3	3	2	2	3	2	1	3	2	1
	>48	4	3	3	4	3	3	3	2	2	3	2	2	3	2	2
Clays C > 35 %	<34	5	5	5	5	5	4	5	4	4	5	4	4	4	3	3
	34-44	5	4	4	5	4	4	4	3	3	4	3	3	4	3	1
	44-55	4	4	3	4	4	3	4	3	3	3	2	2	3	2	1
	>55	4	3	3	4	3	3	3	3	3	3	2	2	3	2	2

*Chemical fertility is decreasing from class 1 to 5

Table 4. Classes of soil intrinsic fertility.*

Number of years N	Classes
<2	C
2-4	B
>4	A

*Intrinsic fertility is decreasing from class A to C.

Table 5. Matrix of soil global fertility.*

Chemical fertility	Intrinsic fertility A	Intrinsic fertility B	Intrinsic fertility C
1	I	I	II
2	I	II	III
3	II	III	III
4	IV	IV	V
5	IV	V	V

* I = high; II = moderately high; III = medium; IV = low; V = very low

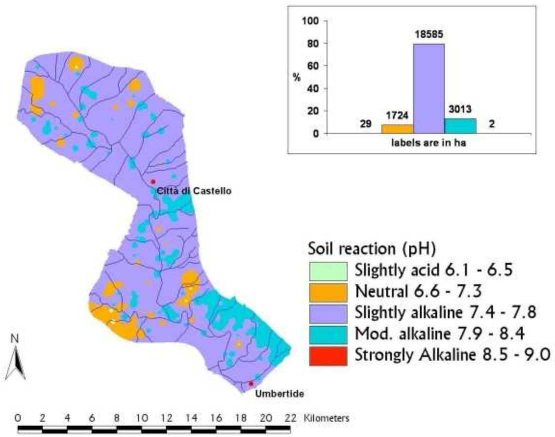

Figure 2. Soil reaction map.

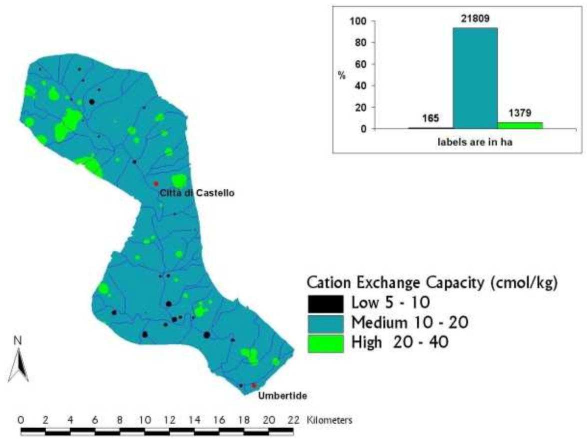

Figure 3. Cation Exchange Capacity map.

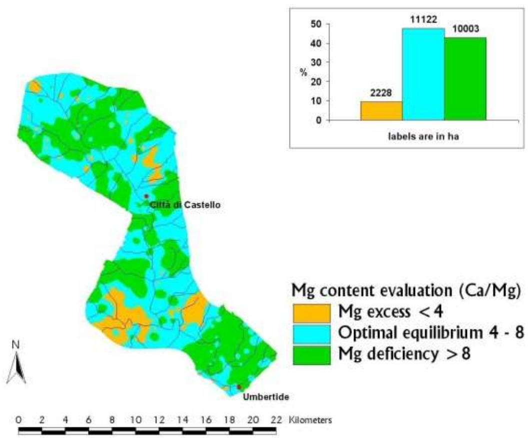

Figure 4. Ca/Mg ratio.

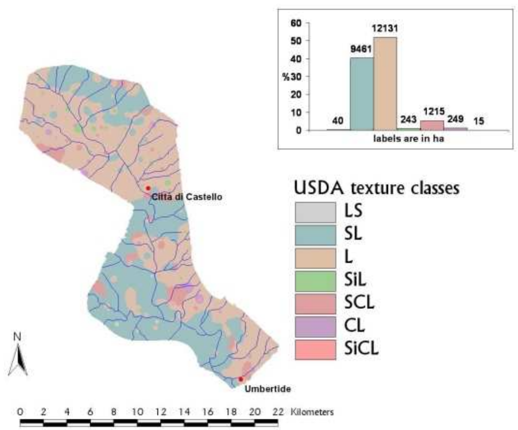

Figure 5. Soil texture map.

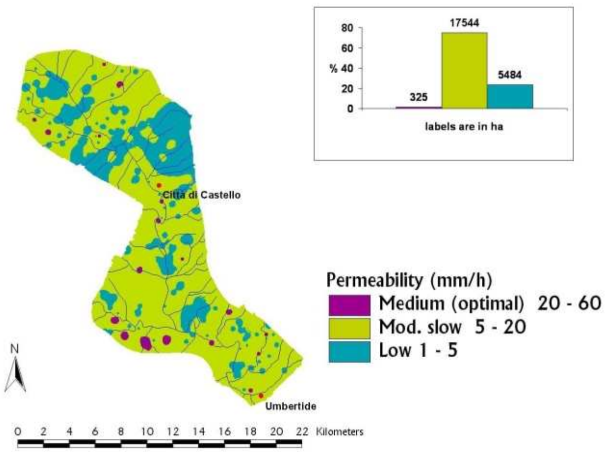

Figure 6. Soil permeability map.

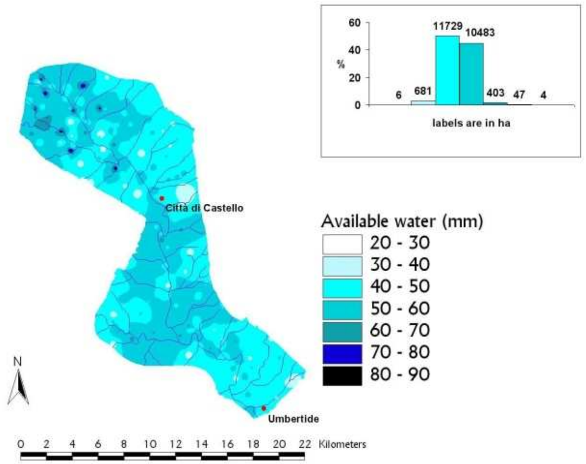

Figure 7. Available Water Content map.

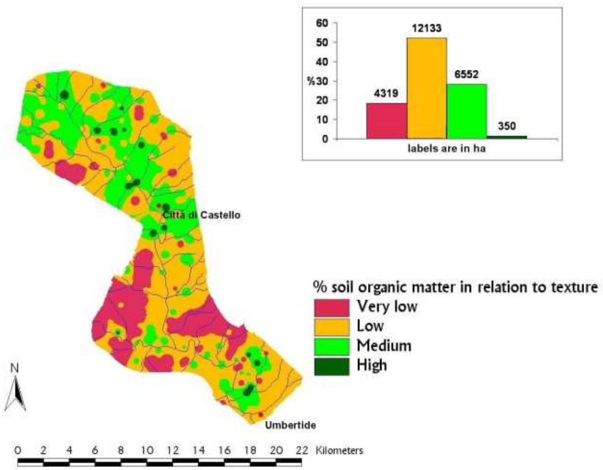

Figure 8. Soil Organic Matter map.

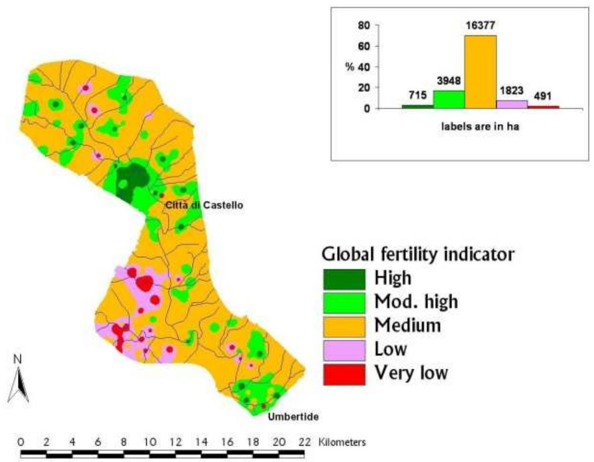

Figure 9. Global soil fertility map.

Conclusions

The selected indicators are to be considered state indicators according to the DPSIR scheme of the European Environment Agency (EEA, 1999a), and are descriptive indicators since they show "what is happening" in the soil (EEA, 1999b). This would suggest the use of an efficiency indicator, which should show if "we are improving" the soil status with proper agricultural practices. A possible representation could be the map of the variations of the indicators with time.

Any negative variation would indicate that agriculture might be no more sustainable in terms of soil quality, and corrective measures should be taken in the short time to prevent its degradation (e.g., soil organic matter depletion). Some recommendations could include soil tests and nutrient management plans, conservation tillage and the adoption of crop rotations. Without these measures, soil degradation will slowly increase due to the same tillage operations, the same type of irrigation system, the same amounts and types of chemical fertilisers without a parallel supply of organic fertilisers, which could improve the soil condition.

Soil protection is not usually the subject of specific measures; rather, it is addressed indirectly through measures directed at the protection of air and water or developed within sector policies (secondary protection, e.g. CAP reform, nitrate directive, sewage sludge directive).

As a consequence, the reversibility of the effects of various threats on soils is an important concept in soil protection. With the aim of maintaining soil's multiple functions, irreversible changes should be avoided if they impair any of its functions, and the ecological ones in particular (i.e. biomass production, filtering, buffering and transformation medium, habitat and gene reservoir).

In some cases, soil properties may return naturally to their normal range of values once the threat is removed. But in many cases, the soil will not return naturally to its original condition, but would do so under appropriate management measures, either by the use of an ecological approach to management, or by the application of technology. Then the main question is the time-scale required. But the problem deserves some attention, since in some cases rehabilitation may not be practicable in economic terms.

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