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"Gheorghe Asachi" Technical University of Iasi, Romania

DIGITAL SOIL MAPPING IN A MOUNTAINOUS AREA WITH MIXED LAND USE (HUMOR CATCHMENT - EASTERN CARPATHIANS, ROMANIA) USING SOIL-LANDSCAPE SYSTEMS, FUZZY LOGIC AND ENVIRONMENTAL COVARIATES

Mihai Niculiță*, Mihai-Gabriel Bălan, Adrian Andrei, Eugen Rusu

Alexandru Ioan Cuza University of Iași, Geography Department, Geography and Geology Faculty, Carol I, 20A, 700505, Iași, Romania

Abstract

The proper evaluation of soil resources, especially in mountainous areas, is very important for the suitable development of the local communities, which host traditional sustainable agriculture. Nonetheless, regarding the preservation of traditional sustainable agriculture and the introduction of a modern development plan to the area, an actualized and detailed distribution of soil cover is crucial. Soil legacy data is not always available at the right scale and spatial cover. To overcome such obstacles, the most suitable approach is the use of digital soil mapping for supplementing soil information. Sparse soil information is available for the Humor catchment, Eastern Carpathians, Romania, therefore we used a soil-landscape system approach, which when coupled with a fuzzy logic-based assignment of soil to landscape system and a raster GIS representation model of the landscape environmental layers (SoLIM model), allow the continuous spatial modelling of the soil classes. The result was validated against available soil maps and soil profiles and it was shown to better represent spatial distribution of the soil cover, although further work is needed to better sample soils representing local conditions which because weren't predictable in the applied model, were included as punctual occurrences.

Keywords: digital soil mapping, environmental covariates, fuzzy logic, soil-landscape systems, SoLIM

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1. Introduction

Soil cover and soil resources are important factors for sustaining human agricultural and forestry practices (Brevik et al., 2015; Csolti et al., 2017), especially in mountainous rural areas with mixed land use (forest and agricultural lands). The available soil information for the Humor catchment is limited to the 1:10 000 soil maps made by the Suceava Office for Pedological Studies (OJSPA) for the agricultural lands from the lower part (30.3%) of the catchment, and to soil descriptions from the Forest Resources Assessments, for every forestry terrain management parcel (with surfaces between 7 and 30 ha) from the forested area of the catchment. Digital soil mapping is widely seen as the best technique for updating soil information using sparse soil legacy data (Evans et al., 2018; Minasny et al., 2008; Rossiter, 2008; Vasiliniuc et al., 2013), or high resolution soil data (Behrens et al., 2014; Häring et al., 2014; Piikki et al., 2015).

Digital soil mapping (DSM) has been used for forest soils with good results (Holleran et al., 2015; Sun et al., 2011; Vasiliniuc et al., 2013), using both knowledge based and statistical models. The basic assumption of modern digital soil mapping is similar to the classic pedogenetic approach of Dokuchaev in 1883 (Florisnky, 2012). This model was further extended by Zakharov in 1927 (Florisnky, 2012), by

*Author to whom all correspondence should be addressed: e-mail: mihai.niculita@uaic.ro; Phone: +40 742 824349; Fax: +40 232 201474

the catena approach (Milne, 1935), by Jenny (1941) CLORPT function (Soil=f {Climate, Organisms, Relief, Parent material, Time}) and later by the soil-landscape systems (Bell et al., 1992; Bell et al., 1994; Hugget, 1975; Ruhe, 1975; Sommer and Schlichting, 1997). McBratney et al. (2003) introduced the SCORPAN functions (Soil class = f {Soil, Climate, Organisms, Relief/Topography, Parent material/lithology, Age, Neighbourhood}; Soil attributes = f{Soil property, Climate, Organisms, Relief/Topography, Parent material/lithology, Age, Spatial position}) to formalize the DSM approach. The difference between DSM and earlier soil mapping is in the technical approach, which requires methods to link the model to the results. The gain is in efficiency, precision, possibility of measuring the uncertainty and reproducibility of the model.

The digital mapping approach can model soil class at any level in a hierarchical classification and soil attributes (McBratney et al., 2003; Odgers et al., 2011a, 2011b). We have chosen to model soil types, according to SRTS 2012 (Romanian Soil Taxonomy System, 2012 version – Florea et al., 2012), which when correlated to World Reference Base for Soil Resources 2015 (IUSS Working Group WRB, 2015), will cover soil groups and also soil subtypes, by the qualifiers. The DSM approach represents the use of a Spatial Soil Information System (SSINFOS) coupled with a Soil Inference System (SSINFERS) to produce digital soil maps (Lagacherie and McBratney, 2007). In the present approach a SSINFOS was created for the Humor catchment, and the SoLIM model (Qi et al., 2006) was used as SSINFERS.

2. Study area

2.1. Pedo-geographic characterization of the study area

The Humor catchment has an area of 106.15 km^2, with a sparse distribution of population totaling about 16900 inhabitants (Romanian Population and Housing Census, 2011). The northern part (94.4%) is occupied by the territory of Mănăstirea Humorului commune which contains three villages, with a sparse population of 3233 inhabitants living from activities like agriculture, agro-tourism and forestry. The touristic town of Gura Humorului is situated in southern part of the study area, at the confluence of the Humor River with the Moldova River.

The Humor catchment is situated in the south-eastern part of the Obcina Mare mountain subdivision, Eastern Carpathians (Fig. 1). The catchment stretches from 471 m a.s.l. in the southern part, at the confluence with the Moldova River, to 1221 m a.s.l. in the north-western part (Fig. 2). The catchment is developed mainly between the 550-900 m a.s.l. altitudes (70.1 %), the altitudes bellow 550 m a.s.l. (5.8 %) appearing only in the southern part. The ridges do not drop below 700 m a.s.l. in the south and eastern part, and under 1000 m a.s.l. in the western and northern part, with altitudes higher than 900 m a.s.l. representing 24.1% of the study area. The Humor River floodplain gently slopes between 800 and 471 m a.s.l. along ~ 22 km.

This catchment overlays Paleocene to lower Miocene flysch deposits (Fig. 3), which represent the external nappes of the Eastern Carpathians, stacked on the pile of basement nappes, which were thrusted eastward over the undeformed foreland deep, represented by the Moldavian Platform (Maţenco and Bertotti, 2000; Săndulescu, 1984). The flysch nappes from the area are represented by Tarcău and Marginal Folds nappes. Tarcău nappe is composed from second-order thrust faults in the form of digitations, and cover Marginal Folds Nappe, which is presented as internal thrusts associated with reverse folds outcropping as half-windows or as rabotage outliers (Maţenco and Bertotti, 2000; Săndulescu, 1984). In the study area, the Tarcău nappe is dominant, while the Marginal Nappe appears at the surface because of erosion, as the Gura Humorului rabotage outlier in the eastern part (Maţenco and Bertotti, 2000; Săndulescu, 1984).

The geologic formations from the study area are described in Table 1. Pleistocene terraces, alluvial fans and colluvium appear mainly in the Humor Valley (Barbu, 1976), while Holocene fluvial sediments are present mainly in the Humor floodplain, downstream of Pleșa village, upstream the channel being developed in bedrock. The same situation appears on the Humor's tributaries, which have Holocene deposits in their lower parts, and channels cut in rock in the medium and upper sectors.

Climatically, the Humor catchment is situated in the continental moderate regime, with influences from by the Baltic and Eastern-European circulation of air masses (Barbu, 1976). The mean multi-annual temperature varies from 4.6°C in the north-western part to 7.5°C in the south (Wordclim database – Hijmans et al., 2005). The monthly mean maximum is in June and the minimum is in January (Barbu, 1976). The number of days with air freeze is 150 in the lower part of the catchment, and can go up to 180 days in the higher north-western part (Barbu, 1976).

Rainfall has a mean multi-annual quantity of 770 mm in the north-western part, which decreases to the south where 630 mm falls (Wordclim database – Hijmans et al., 2005). The annual distribution of rainfall is given by the single maximum, which stretch from May to August, while snow falls between the end of September until May (Barbu, 1976).

The vegetation is characterized by the presence of mesofil deciduous forests and mixed forests at the contact with the coniferous forests level (Barbu, 1976), with four associations described by Chifu and Șurubaru (1999) and presented below. In the eastern part, at the contact with the Moldavian Plateau, in valleys between 450 and 550 m, pure beech forest (*Fagus sylvatica*, *Fagus taurica*) appears. Also in the eastern part, at 450 to 600 m a.s.l., on ridges and hillslopes, a forest of beech (*Fagus sylvatica*, *Fagus taurica*) and common hornbeam (*Carpinus betulus*) intermix with the previous level.

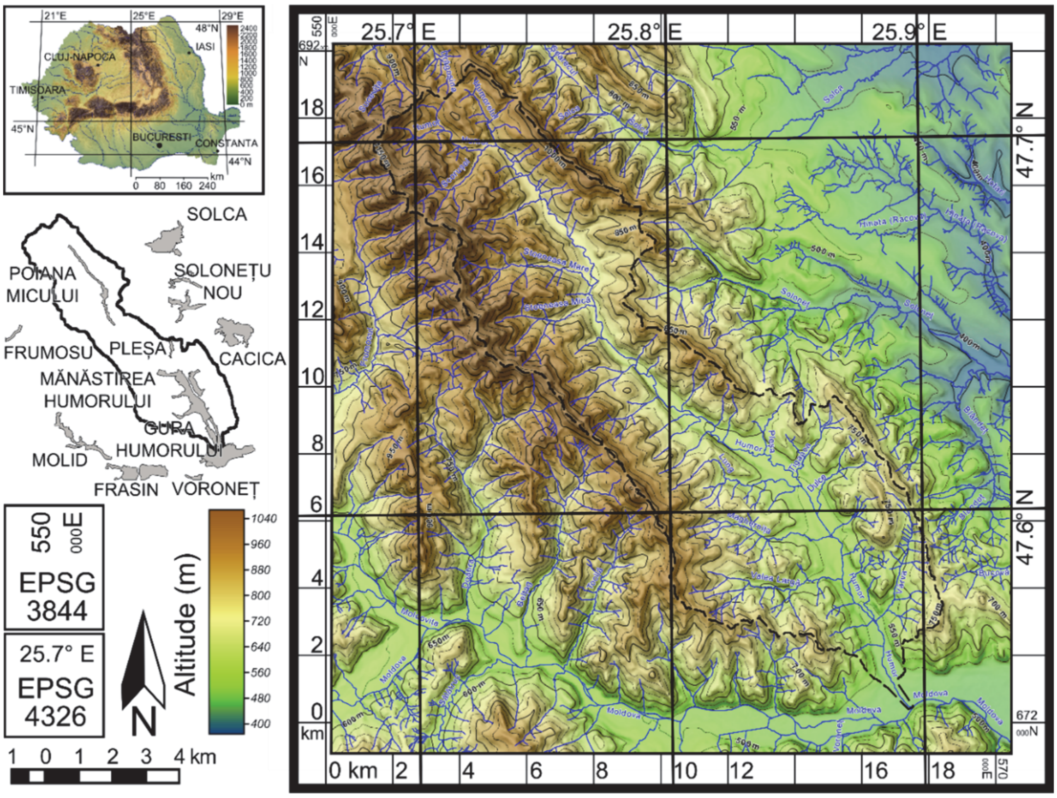

Fig. 1. Geographical position of the study area

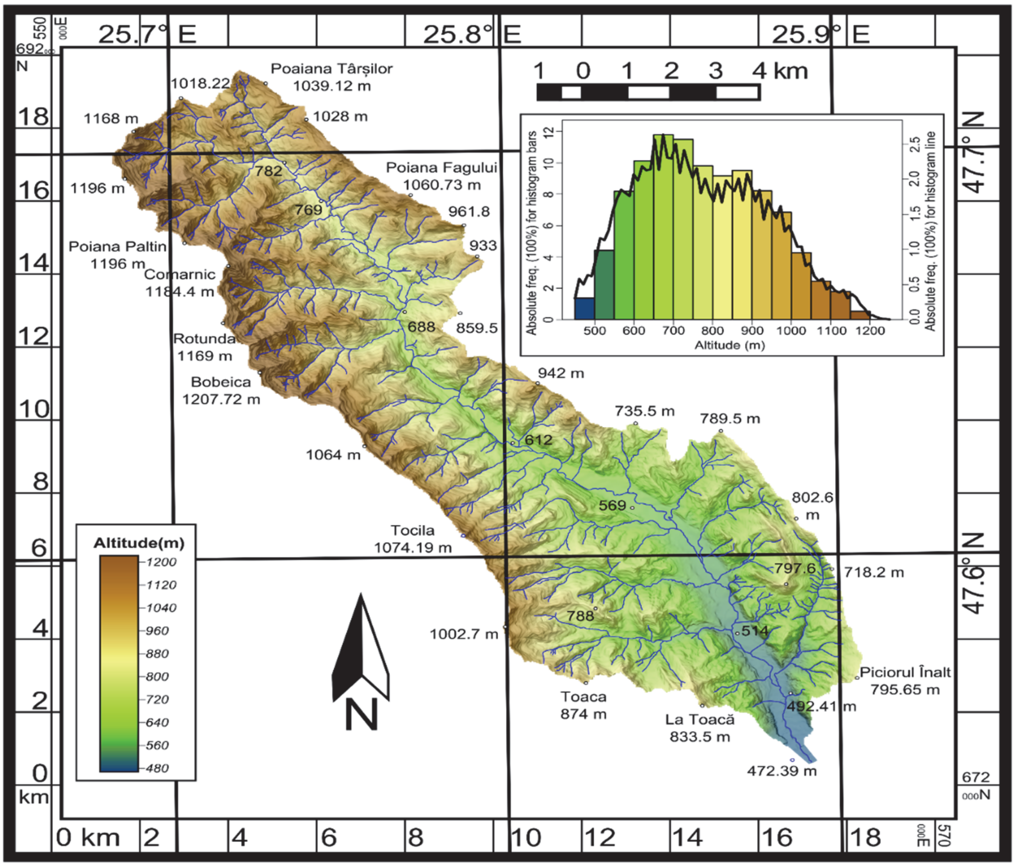

Fig. 2. Shaded DEM for the study area

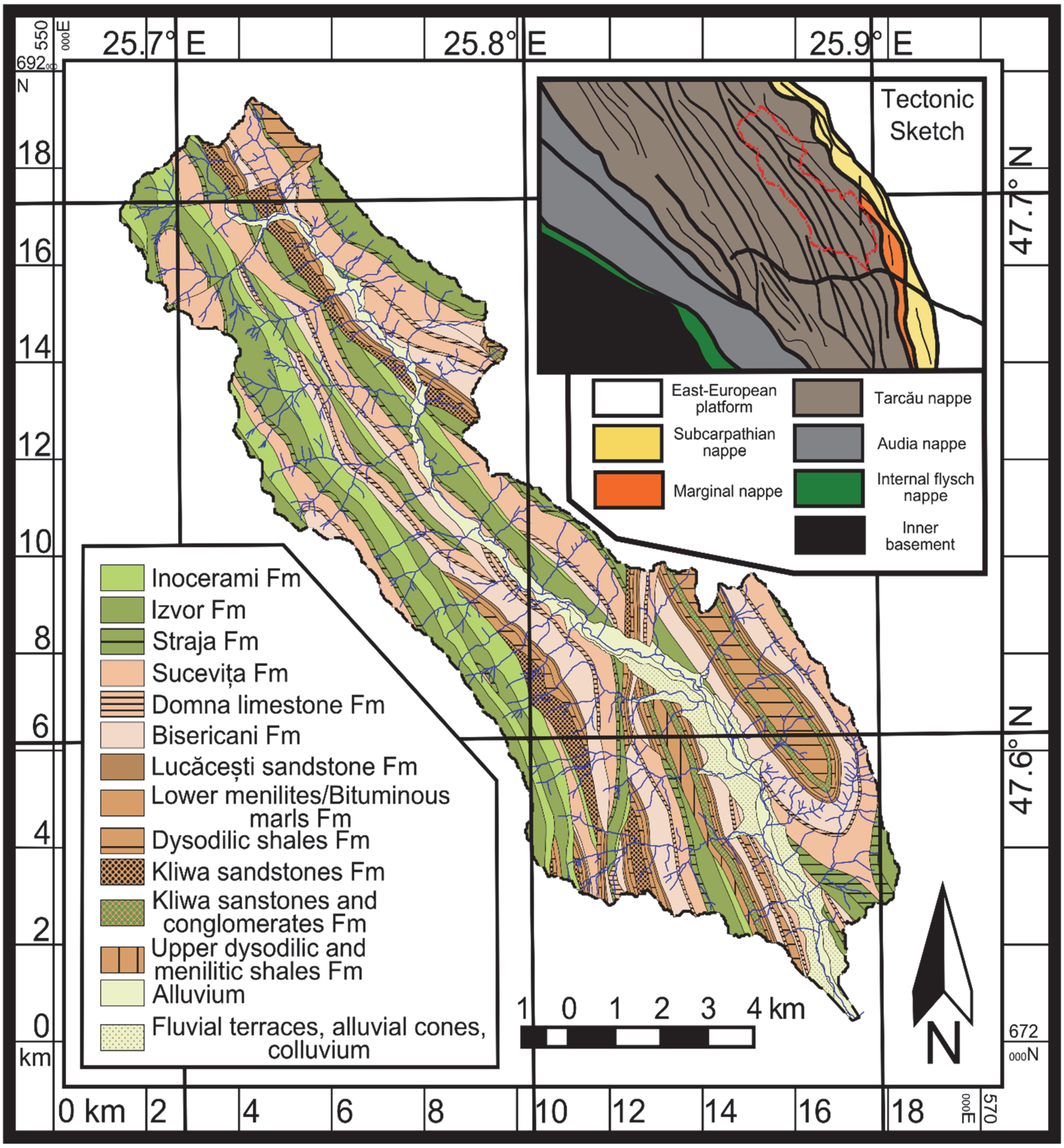

Fig. 3. Geologic map of the study area (redrawn after Ionesi, 1971 and Joja et al., 1984; the tectonic sketch after Săndulescu, 1984 and Mațenco and Bertoti, 2000)

Table 1. Descriptions of the geologic formations in the study area (Ionesi, 1971; Grasu et al., 1988)

Formation Name	***Age***	***% of Study Area***	***Description***
Inocerami Fm.	Senonian	9.4	mainly marls, associated with calcareous marls, limestones and microconglomerates
Izvor Fm.	Paleocene	9.1	mainly limestones (biosparites and sparites), associated with siltstones, shales and marls
Straja Fm.	Paleocene	2.5	mainly sandstones (quartz arenites), with subsequent siltstones and clay shales
Sucevița Formation	Eocene	11.4	mainly clays and marls, with sandstones (arenite, calcareous, ruditic) and limestone (biosparites)
Doamna Limestone Fm.	Eocene	2.3	dominated by limestones (biosparites), but also contains carbonate sandstones, marls and siltstones
Bisericani Fm.	Eocene	6.8	mainly clays and marls
Lucăcești Sandstone Fm.	Eocene	1.1	mainly sandstone (quartzarenite)
Lower Menilites Fm.	Oligocene	1.7	shales and menilites, with intercalations of sandstones (feldsarenites)

Lower Dysodilic Shales Fm.	Oligocene	3.4	mainly clayey shales with intercalation of sandstones (wacke, arenites)
Kliwa Sandstone Fm.	Oligocene	4.9	mainly sandstones (quartz arenite)
Kliwa Sandstone Fm. replaced by conglomerates with green schists	Oligocene	5.8	conglomerates with green schists
Upper Dysodile and Menilites Fm.	Miocene	4.7	mainly mudstones, clay shales and marls
Terraces, alluvial fans and colluvium	Pleistocene	14.5	gravels
Fluvial sediments cover	Holocene	22.4	gravels

**Fm = Formation*

Over 600 m a.s.l., covering the majority of the study area, the mixed forest appears, and is constituted mainly of beech (*Fagus sylvatica*) with silver fir (*Abies alba*) in the east and Norway spruce (*Picea abies*) in the west parts of the study area. Over 900-1100 m a.s.l., on steep hillslopes with north exposures, beech forests (*Fagus sylvatica*) with reduced arbustive and acidophil herbaceous layers (*Vaccinium, Picea*) appear.

Pastures develop on deforested lands (Barbu, 1976), associations with *Festuca rubra* being characteristic under deforested Norway spruce lands, while associations with *Agrostis tenuis* (plus *Festuca rubra*, *Cynosurus cristatus*, *Arrhenatherium elatius* and *Festuca pratensis*) common under deforested beech and silver fir lands. Associations with *Nardus stricta* appear on acid soils and overgrazed pastures, while on recent deforested lands, the pastures contain associations of *Calamagrostis arundinaceea* (under Norway spruce forest) and *Arrhenatherium elatius* (under beech and mixed forest). On moderately wet and acid soils, associations of *Trisetum falvescens*, *Deschampsia caespitosa*, *D. flexuosa* and *Molinia coerulea* appear, while at hillslope bases, terraces and well drained floodplains, the pastures have *Festuca pratensis*, *Cynosurus cristatus*, *Lolium perennis* and *Alopecurus pratensis*. On Gleyosols and wet floodplains areas, associations of *Carex sp.*, *Scirpus silvaticus*, *Eriophorum latifolium*, and *Gliceria plicata* grow.

The soil covers of the Humor catchment (Fig. 4, all soil classes are named *sensu* SRTS 2012 – Florea et al., 2012 and are correlated with WRB 2015- IUSS Working Group WRB, 2015) is dominated by Cambisols, which are in their optimum climatic area, at 580-1300 m a.s.l. (Barbu, 1976; Barbu et al., 1981; Lupașcu et al., 1986), and appear mainly on slope deposits as poorly developed soils. Eutric Cambisols (with base saturation level > 53 %, according to the Romanian Soil Taxonomy System - Florea et al., 2012) are characteristic at the 580 and 1300 m a.s.l. level, while Dystric Cambisols (base saturation level >60%, according to the Romanian Soil Taxonomy System (Florea et al., 2012), develop between 900 and 1350 m a.s.l. (Lupașcu et al., 1986).

Podzols and Entic Podzols appear (Gavriluț, 1987), all over the study area, at altitudes lower than the 1100 (on metamorphic deposits) - 1350 (on flysch deposits) m a.s.l. climatic optimum (Lupașcu at. al., 1986) of the area, mainly in areas of siliciclastic sandstone lithology. There are cases of Podzols at lower altitudes (down to 550 m), also related to siliciclastic sandstones (Gavriluț, 1987; Lupașcu et al., 1986). Under 580 m a.s.l. Luvisols and Haplic Luvisols develop, mainly in the central, southern and eastern part of the catchment (Florea et al., 1991; Gavriluț, 1987). Leptosols occur on steep slopes where sandstone, conglomerate and limestone outcrops (Florea et al., 1991). There are also areas covered by Regosols, where the slope deposits are thicker and are composed of loamy to sandy deposits (Gavriluț, 1987). Gleysols and Stagnosols appear on hillslopes and floodplains, where water saturation is present (Gavriluț, 1987). Fluvisols appear on the Humor and its tributaries floodplains, in the proximity of the active channels (Gavriluț, 1987).

Land use in the study area (according to CLC 2006 data – European Environment Agency, 2006) is dominated by mixed forests (27.8 %), coniferous forests (27 %) and by broad leaved forests (7.4 %). Natural grassland (1.3 %) and transitional woodland-shrub (3.4 %) appear in deforested areas on steep hillslopes, while pastures (14 %) appear on deforested gentle hillslopes and on fluvial terraces. Agricultural terrains with significant areas of natural vegetation (4 %) and complex cultivation patterns (6.3 %) appear mainly in the Humor and tributaries floodplains and on fluvial terraces. Discontinuous urban fabric (8%) is represented by the Gura Humorului city and the villages from Mănăstirea Humorului municipality. Humor and tributaries channels occupy 0.8 % of the study area.

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3. Material and methods

3.1. DEM

The Digital Elevation Model (Fig. 2) was obtained through interpolation from contour lines and height points digitized from 1:5 000 topographic maps using multilevel B-spline (Lee at al., 1997) implemented in SAGA GIS 2.12. This method imposes spline functions on different scaled levels, by which the roughness of the surface is controlled. The chosen level was 14, the maximum possible level in the SAGA implementation, to obtain all the features represented by the contours.

B-spline refinement was also used to keep the surface from crossing through the contours. Undershoots, overshoots, padi terraces and other unusual features which can be attributed to the interpolation artifacts, were checked manually and we noted their absence.

3.2. Environmental covariates

The DEM was used to derive the slope, catchment area and topographic wetness index, which were used as environmental covariates. Slope was computed using the Maximum Triangle Slope (Tarboton, 1997) for obtaining slope values spread better along the 0-90° interval. We didn't used the Smith et al. (2006) and Zhu et al. (2008) approach of computing slope using big window kernels, because we believe that this setting works well with statistical methods such as regression, where outliers break the fit of the model. In our case, slope is used together with geology for delineating the presence of Leptosols, which occur in single pixels, so the precise shape of the pixel neighborhood needs to be computed.

We chose to use the SAGA implementation of Wetness Index calculation. This implementation uses a Modified Catchment Area method (Böhner and Selige, 2006) which simulates the water diffusion in floodplains by modifying catchment area in these regions using slopes values, in an interactive way, until the values of the catchment areas reach the maximum values of the channels nearby. In this way that the flat areas will have large catchment areas, similar to those of nearby channels.

To apply the soil catena relationships, we also created a geomorphometric classification for the delineation of the catena based landforms. Ridges and channels were separated using the hydrological criteria of catchment area: ridges are pixels with catchment areas under 125 m^2, while channels are pixels with catchment areas bigger than 2800 m^2 (limit determined by iteratively checking that the results of the channel extraction is consistent with the position of channels visible in the DEM morphology). The areas in between are considered hillslopes. The radius of 1 m variance of elevation computed for 100 pixels around a certain pixel was used to classify flat areas which were further classified as floodplains, terraces and plateaus, based on the relative altitude to channel network: floodplains are adjacent to channel, at relative altitude under 10 m, terraces are adjacent to the floodplain, at relative altitudes of 2 to 35 m. Barbu (1976) states that the higher Humor terrace have 35 m relative altitude and plateaus are at relative altitudes larger than 35 m.

Because only the Humor River has terraces in the study area (Barbu, 1976), the relative altitude was computed toward the Humor's channel. The hillslope class was separated into upper (shoulder), median (backslope) and lower landscape positions, based on the curvature classification of Schmidt and Hewitt (2004).

Also from Schmidt and Hewitt (2004) classification peaks and pits were defined.

3.3. SoLIM methodology

The SoLIM methodology for soil mapping (Qi et al., 2006) is a method based on fuzzy theory and prototype category theory.

Both theories are used to deal with the inherent uncertainty of membership of soil classes in genetic soil classification. The prototype categories are conceptual entities used to model soil classes, and fuzzy theory is used to assign the degree of membership to a certain class, based on the conceptual relation between soil pedogenetic factors and the soil cover.

After the fuzzy rules were defined for every prototype category/soil class, the inference process is applied for every pixel.

For every pixel the similarity vector for a certain class is computed, and through defuzzification, every pixel is assigned the soil class of the highest membership values from the similarity vectors. SoLIM Solution 5.0 software (http://solim.geography.wisc.edu/software/), which implements the SoLIM model, was used to create the rules, to generate the inferences (raster representation of the similarity vectors) and the hardened map (raster representation of the defuzzification).

3.4. Soil-landscape systems

The soil information available for the Humor catchment is composed of legacy soil maps (Fig. 4 - the 1:200 000 soil map covering all the study area and the 1:10 000 soil map covering the agricultural terrains of Mănăstirea Humorului commune), legacy soil profiles (Fig. 4–7 probed in 2014 by the authors, 5 described by Barbu, 1976 and 265 described by Gavriluț, 1987) and the soil-landscape systems which can be identified in the literature and in the text attached to the legacy soil maps. The analysis of the Gavriluț (1987) legacy soil profiles (Fig. 5 - 265 soil profiles described, from which 62 have soil analytic properties measured) does not fully sustain the literature's pedo-geographic model from the literature (Barbu, 1976; Barbu et al., 1981; Florea et al., 1991; Lupașcu et al., 1986).

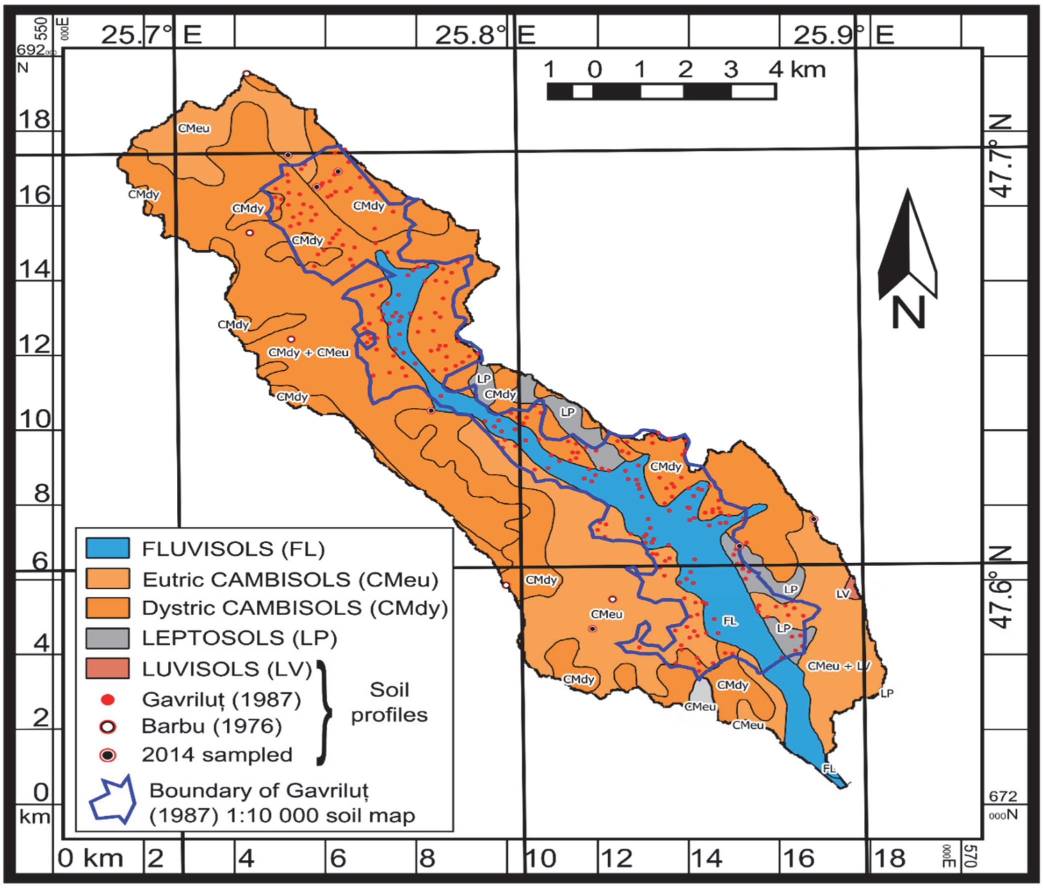

Fig. 4. Soil map of the study area (redrawn after 1:200k Florea et al., 1991 soil map)

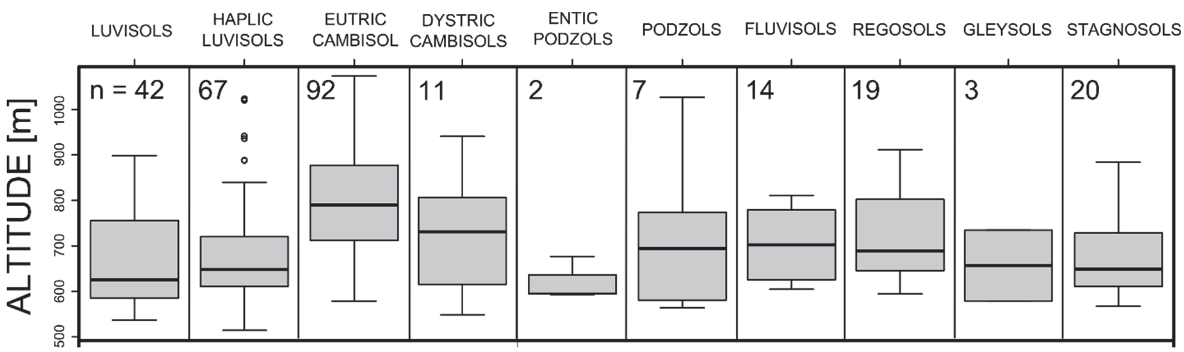

Fig. 5. Boxplots of altitude distribution for the legacy soil profiles

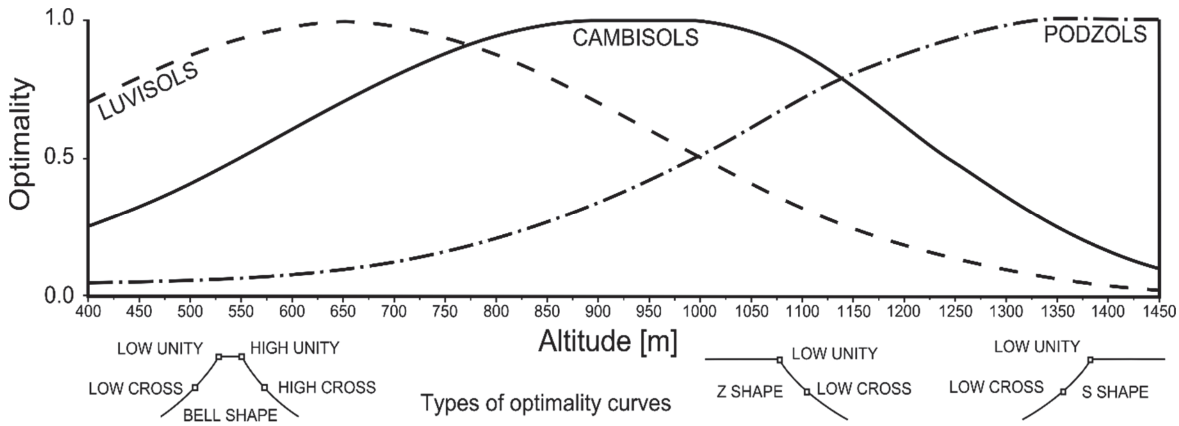

Fig. 6. The fuzzy rules of the zonal soils according to altitude

Also, because the soil sampling spatial distribution is not evenly distributed (with more samples in non-forested areas and no statistical inference regarding the significance of the sampling), we chose to use only the soil classes as the target of the digital soil mapping. In addition, soil types (equivalent to varieties in WRB 2014) were merged to soil classes, because there is no pedo-geographic information in the used covariates to differentiate between soil types which appear in similar pedo-geographic domains (Regosols cannot be differentiated from Leptosols, because both appear on slopes where there is a shallow alteration deposit over the rock; Eutric Cambisols and Dystric Cambisols are differentiated only by chemic properties; Haplic Luvisols vs. Luvisols and Entic Podzols vs. Podzols are hard to differentiate using covariates because the single difference between them is the intensity of the pedogenesis; Gleysols and Stagnosols are hard to differentiate by water flow analysis on DEM, because they appear both on floodplains and on hillslopes).

The regional soil landscape system is characterized by a gradient, given by the altitude, temperature and precipitation, from north-west to south east, from Podzols to Cambisols and to Luvisols, which is interrupted by patches of soils influenced by geology, landforms or other local conditions.

In the fuzzy rules, altitude was used as the main criteria for mapping the zonal levels of Cambisols, Luvisols and Podzols (Fig. 6). For Cambisols, an optimality curve of bell shape was used, with low cross at 550 m a.s.l., high cross at 1250 m a.s.l., low unity at 900 m a.s.l. and high unity at 1000 m a.s.l. Luvisols were modeled with an optimality curve of bell shape with low cross at 300 m a.s.l., high cross at 1000 m a.s.l. and low unity and high unity both at 600 m a.s.l. Podzols were modelled with an S shape, with low cross at 1000 m a.s.l. and low unity at 1350 m a.s.l.

Gleysols/Stagnosols cannot be differentiated from each other and they appear mainly due to local morphology and geologic deposits, in depression areas both on floodplains and hillslopes (as the pedo-geographic model state and the soil legacy data shows). We used Topographic Wetness Index values fitted with an optimality curve of S shape with 7 low cross and 11 low unity vales. As an enumerated rule the following landforms types were used with one optimality value: floodplains, terraces, ridges, plateaus and backslopes. Leptosols and Regosols appear on steep slopes where bedrock is close to the surface, on rocky geologic deposits. The optimality curve for these soils was setup as an S shape for slope, with low cross at 10° and low unity at 15° values, and with an enumerated rule for shoulders and backslope landform types.

Fluvisols develop on floodplains in the proximity of the active channel of the Humor River and its tributaries. Optimality curves of vertical (Z shape with low cross of 10 m and low unity of 20 m) and horizontal distance to the river channel (Z shape with low cross of 1 m and low unity of 2 m) were used to map these soils. The presence of a mapped channel according to the landform classification was also used as an enumerated rule (with 1 optimality value).

For all the legacy soil profiles occurrences rules with impact radius of 50 m and distance similarity with linear effect were also defined.

4. Results and discussion

The results of the SoLIM model are presented as a hardened raster in Fig. 7. The altitudinal zonation of the Podzols, Cambisols and Luvisols is evident and compared with the soil legacy maps include both Podzols and Luvisols, which weren't displayed on the same map in any of the legacy soil maps. Of the Luvisol legacy soil profiles, 17 were incorrectly modelled (16%) while 92 were correctly modeled (84%). For Cambisols 53 (51%) of the profiles were correctly identified, the remaining 50 (49%) profiles were incorrectly identified, mainly as Luvisols.

The model assumed that in the south-western part of the study area, at low altitudes was the Luvisols level, and the Cambisols which appeared here (confirmed by the soil legacy profiles) were related to geology and geomorphologic conditions, on hillslopes with slope deposits and where the pedogenesis is not so evolved (but evolved enough not so define the soils as Regosols). In the present approach we addressed this situation by including the Cambisols legacy soil profiles as punctual occurrences in the Luvisols area.

The model failed to represent the distribution of the other soils: the validation against the legacy soil profiles showing that none of them were predicted. We believe that this situation is related to the non-representative sampling of the legacy soil study and to the difference in scale between the two approaches. Our digital soil map target was the 1:100 000 scale, and was limited to the resolution of the environmental covariates used. The soil information contained in the soil legacy profiles was incorporated into the model by using the occurrence rules.

The validation of the digital soil map against the 1:10 000 soil map revealed the patchy nature of the legacy soil map, which is a further indication of the difference in scale and resolution. Nonetheless, the model managed to fit the distribution of zonal soil classes, opening the possibility to improve soil knowledge in the study area. The presence of a mosaic of soils and conditions in the lower parts of the catchment show the need for further studies, but also supports the need for a consistent modelling framework methodology which is guaranteed by the use of digital soil mapping.

5. Conclusions

A set of soil-landscape systems were defined for the Humor catchment and were used together with the fuzzy rule system of the SoLIM model and environmental covariates to digitally map the soils in the study area.

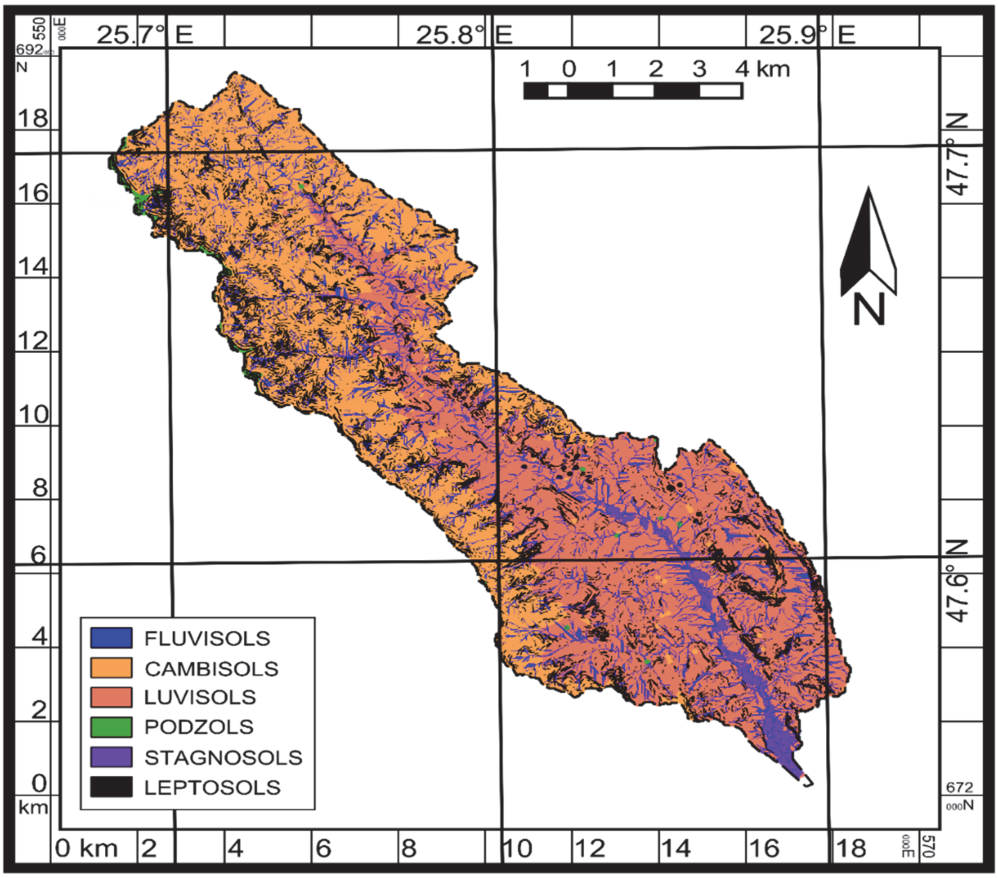

Fig. 7. The digital soil map

The results were validated against a soil map of the area at 1:10 000 scale and legacy soil profiles. The validation showed that the approach produced good results for zonal soil classes, but did not manage to explain the distribution of soil types related to local conditions. The presented model can be seen as a general soil framework, on which any further acquired soil knowledge can be integrated.

The results presented in this work can be further used in environmental assessments and to apply land suitability indices regarding the assessments of the major cultivated crops and the suitable for forestry species. At the same time, more studies are also needed for optimal soil sampling in order to explore the soil-landscape systems (especially along catenas), needed for resolving the spatial distribution of soil varieties.

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