Chapter 33
Synthesis and Conclusions

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Abstract The book contains a preface and 33 chapters that cover a large array of subjects including the basics of geopedology, implementation methods and techniques, and applications in land degradation and land use planning. Subjects addressed by the contributing authors are diverse but complementary. This shows that geopedology can be seen as a far-reaching discipline to support the inventory, scientific study, and practical management of natural resources. Geopedology aims at integrating soils and geoforms, two basic components of the earth's epidermis. Sets of examples that use different modalities or variants of geopedology are presented, from open soilscape approach for scientific research, to a more structured survey approach for mapping purposes.

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33.1 Introduction

The book contains a preface and 33 chapters that cover a large array of subjects including the basics of geopedology, implementation methods and techniques, and applications in land degradation and land use planning. Subjects addressed by the contributing authors are diverse but complementary. This shows that geopedology can be seen as a far-reaching discipline to support the inventory, scientific study, and practical management of natural resources. Geopedology aims at integrating soils and geoforms, two basic components of the earth's epidermis. Commonalities between the subjects treated in the book allowed grouping them into five thematic parts; their relevant features are highlighted hereafter.

33.2 Part I: Foundations of Geopedology

The first part of the book written by Zinck deals with the basics of geopedology: its relationships with soil geomorphology, its focus and aims, its place in the pedologic landscape, and its supporting geomorphic framework.

After two initial chapters introducing the structure of the book, a brief review of the relationships between geomorphology and pedology is presented in Chap. 3. These relationships including the conceptual aspects and their practical implementation in studies and research have been referred to under different names, the most common expression being *soil geomorphology*. Definitions and approaches are reviewed distinguishing between academic and applied streams. There is consensus on the basic relationships between geomorphology and pedology: geomorphic processes and resulting landforms contribute to soil formation and distribution while, in return, soil development has an influence on the evolution of the geomorphic landscape. However, there is still no unified body of doctrine, in spite of a clear trend toward greater integration between the two disciplines. There are few references in international journals that provide some formal synthesis on how to carry out integrated pedogeomorphic mapping.

Chapter 4 outlines the essence of the geopedologic approach in conceptual, methodological, and operational terms. Geopedology is based on the conceptual relationships between geoform and soil which center on the earth's epidermal interface, is implemented using a variety of methodological modalities based on the three-dimensional concept of the geopedologic landscape, and becomes operational primarily within the framework of soil inventory, which can be represented by a hierarchic scheme of activities. The approach focuses on the reading of the landscape in the field and from remote-sensed imagery to identify and classify geoforms, as a prelude to their mapping along with the soils they enclose and the interpretation of the genetic relationships between soils and geoforms. There is explicit emphasis on the geomorphic context as an essential factor of soil formation and distribution. The geopedologic approach is essentially descriptive and qualitative. Geoforms and soils are considered as natural bodies, which can be described by direct observation in the field and by interpretation of aerial photographs, satellite images, topographic maps, and digital elevation models.

The pedologic component of geopedology is described in Chap. 5, with special consideration to the organization of the soil material in the pedologic landscape. Soil material is multiscalar with features and properties specific to each scale level. The successive structural levels are embedded in a hierarchic system of nested soil entities or holons known as the holarchy of the soil system. At each hierarchic level of perception and analysis of the soil material, distinct features are observed that are particular to the level considered. The whole of the features describes the soil body in its entirety. Each level is characterized by an element of the soil holarchy, a unit (or range of units) measuring the soil element perceived at that level, and a means of observation or measurement for identifying the features that are diagnostic at the level concerned. The holarchy of the soil system allows highlighting relevant relationships between soil properties and geomorphic response at different hierarchic levels. These relationships form the conceptual essence of geopedology.

The following three chapters refer to the geomorphic component of geopedology, considering successively the criteria for classifying geoforms, the classification of the geoforms, and the attributes of the geoforms. Chapter 6 describes how the combination of basic taxonomic system criteria with the hierarchic arrangement of the geomorphic environment determines a structure of six nested categorial levels. Geoforms have distinct physiognomic features that make them directly observable through visual and digital perception from remote to proximal sensing. Changing the scale of perception changes not only the degree of detail but most significantly the nature of the object observed. The geolandscape is a hierarchically structured and organized domain. Therefore, a multicategorial system, based on nested levels of perception to capture the information and taxonomic criteria to organize that information, is an appropriate frame to classify geoforms. Categorial levels are identified by their respective generic concepts, including from upper to lower level: geostructure, morphogenic environment, geomorphic landscape, relief/molding, lithology/facies, and the basic landform or terrain form.

Chapter 7 attempts to organize existing geomorphic knowledge and arrange the geoforms in the hierarchically structured system with six nested levels introduced in the foregoing Chap. 6. Geoforms are grouped thematically, distinguishing between geoforms mainly controlled by the geologic structure and geoforms mainly controlled by the morphogenic agents. It is thought that this multicategorial geoform classification scheme reflects the structure of the geomorphic landscape sensu lato. It helps segment and stratify the landscape continuum into geomorphic units belonging to different levels of abstraction. This geoform classification system has shown to be useful in geopedologic mapping, and it offers great potential for digital soil mapping.

Attributes are needed to describe, identify, and classify geoforms. These are descriptive and functional indicators that make the multicategorial system of the geoforms operational. Four kinds of attribute are used as outlined in Chap. 8: morphographic attributes to describe the geometry of geoforms; morphometric attributes to measure the dimensions of geoforms; morphogenic attributes to determine the origin and evolution of geoforms; and morphochronologic attributes to frame the time span in which geoforms originated and evolved. The morphometric and morphographic attributes apply mainly to the external component of the geoforms, are essentially descriptive, and can be extracted from remote-sensed imagery or derived from digital elevation models. The morphogenic and morphochronologic attributes apply mostly to the internal component of the geoforms, are characterized by field observations and measurements, and need to be substantiated by laboratory determinations.

33.3 Part II: Approaches to Soil-Landscape Patterns Analysis

Soil-landscape patterns can be analyzed in terms of spatial distribution, temporal evolution, or more advantageously a combination thereof. Part II presents a variety of approaches to establish and analyze relationships between soil and landscape in space and time. Information and knowledge can be obtained from field observation and landscape reading through systematic survey or transect description or a combination of both. A less common modality to identify patterns consists in translating the farmers' mental maps into soil-relief maps. Existing soil and soil-geomorphology maps are valuable sources of information; their interpretation reveals soil-landscape patterns not only in terms of geographic distribution but also in terms of temporal evolution. The concept of pattern suggests usually diversity: pedodiversity and geodiversity can be described using landscape ecology metrics.

In Chap. 9, Barrera-Bassols conveys findings from an integrated participatory soil-landscape survey in an indigenous community of central Mexico, combining ethnopedologic and geopedologic approaches. He describes the soil-landscape knowledge that local people use for selecting suitable agro-ecological settings, applying land management practices, and implementing soil conservation measures. Relief and soil maps generated by both procedures, the indigenous and the technical, are compared, and the level of spatial correlation of the map units is assessed. Commonalities, differences, and synergies of both soil knowledge systems are highlighted.

Diversity analysis of natural resources attempts to account for the variety of forms and spatial patterns exhibited by natural bodies, biotic and abiotic, at the earth's surface. Recently pedologists drew attention to soil diversity analysis and modelling using statistical tools similar to the ones used by ecologists, reporting insightful relations between spatial patterns of soil and vegetation. Geodiversity studies are mostly concerned with the preservation of the geological heritage, bypassing most of the aspects related to its spatial distribution. In Chap. 10, Ibañez and Pérez Gómez explore a novel perspective of integrating soils, geoforms, climate, and biocenoses in a holistic approach to describe the structure and diversity of the earth surface systems.

Chapter 11 outlines a new sedimentological and geopedologic approach that explains more accurately soil development and spatial distribution in a sub-region of the Pampa plains in central Argentina. According to the traditional interpretation, vertic properties of the Pampa soils are due to a combination of finer parent materials resulting from granulometric selection during eolian transport from the south-western Andean sources and intense smectite formation in a more humid eastern sector of the Pampa. In contrast to this view, Morrás and Moretti provide data that sustain a different soil-landscape evolution model. Smectitic sediments originating from northern sources in the Paraná basin were deposited in the Rolling Pampa and later covered by illitic loess sediments from south-western Andean sources. During a subsequent humid period in the Holocene, the illitic sediments were eroded and the smectitic sediments were exposed on the upper parts of the undulating relief. As a result, Typic Argiudolls developed on the illitic and volcanoclastic Andean sediments, while vertic soils evolved in higher positions of the landscape on the smectitic sediments of older age and different origin.

In Chap. 12, Pain et al. describe the landforms and soils in the arid region of the northern United Arab Emirates, and show how their form and evolution are closely related. Eight soil types were recognized at great group level, while 28 soil series were identified and grouped into 42 map units, each consisting of two or more soil series and a number of minor soil inclusions. At subgroup and family levels, these soils are related to specific landform morphologies and processes. Indeed, the example shows that although rainfall is scanty in this desert environment, the recognition of calcic and gypsic horizons clearly demonstrates that soil forming processes have been operating over a period of time.

Geopedology integrates an understanding of the geomorphic conditions under which soils evolve with field observations. In Chap. 13, Rossiter discusses examples from exhumed paleosol areas, low-relief depositional environments, and recent post-glacial landscapes, where simplistic digital soil mapping would fail but geopedology would succeed in mapping and explaining soil distribution. Mapping of soil bodies, not properties in isolation, is what gives insight into the soil landscape. Attempts at correlating environmental covariates from current terrain features, vegetation density, and surrogates for climate cannot succeed in the presence of unmapped variations in parent material, soil bodies, and landforms inherited from past environments.

In Chap. 14, Saldaña describes the effect of scale on the integration of landscape ecology with soil science principles, and emphasizes soilscape-pattern analysis complemented with the application of landscape ecology metrics. The approach is tested in the Jarama-Henares interfluve, central Spain, where all metrics showed to be scale-dependent, with higher values obtained at local scale. In addition, the number of indices required to describe appropriately the soilscape patterns was smaller at local than at regional scale.

Soils by virtue of their parent materials can provide key information about past sedimentologic or geologic processes and systems. Geologic and geomorphic processes substantially, but not solely, determine the materials from which soils are derived via the nature and redistribution of sediments. In Chap. 15, Schaetzl and

Miller focus on examples of studies or situations where careful examination of uniform parent material type and distribution can provide important information about the geomorphic attributes and history of the landscape. The relationship found between soils and their parent materials connects soil survey maps and geological maps. Different information collected for, and represented by, the respective maps – due to differences in purpose, focus, or resources – can assist the investigations of other disciplines. This multiple utility is especially true for studying soil-landform assemblages and soil-landscape evolution.

Chapter 16 of Yemefack and Siderius describes the application of a geopedologic approach for delineating and characterizing soil units and related soil fertility in tropical forest highlands of northern Thailand. A mathematical approach for analyzing relations between individual soil bodies was applied to study soil fertility variation as related to the categorial levels of a hierarchic geoform classification system. This relationship was displayed by means of numerical values of the Similarity Index (SI) and the Fertility Distance (FD), computed by integrating eight soil properties (pH, C, N, K, CEC-soil, CEC-clay, clay, and base saturation) assumed to influence soil fertility. The study revealed that the geopedologic approach for characterizing soils of this complex area was suitable and allowed the results obtained in sample areas to be extrapolated to similar areas. It has the advantage of being based on strong integration of geomorphology and pedology, and of considering the parent material at lower categorial levels of the system.

33.4 Part III: Methods and Techniques Applied to Pattern Recognition and Mapping

Part III comprises a set of chapters dealing with different spatial modelling techniques for soil pattern recognition and mapping, and the characterization of soil properties relevant for soil environmental risk management. A commonality between the case studies is the use of digital elevation models, remote-sensed imagery, digitally processed data using GIS, and spatial analysis and modelling techniques to transform data into usable information.

Soil classification deals with the systematic categorization of soils based on distinguishing characteristics as well as criteria that dictate choices in land use. In Chap. 17, Angueira et al. use DEM map derivatives, multi-spectral, multi-temporal and multi-spatial resolution satellite images, and visual interpretation techniques to enhance identification and classification of landscapes and soils. They describe major soil and land characteristics in a semiarid area of the Argentinean Chaco that has undergone intensive land use changes from forest to commercial agriculture over the last decade. These changes and the lack of reliable soil information at suitable scales are threatening sustainable development of the region and raising social conflicts. Map units were determined based on the integration of geoforms and soils, knowledge of landscape and soil forming factors, with the support of remote sensing data and modern survey techniques.

Quality of soil maps can be assessed from the producer's and the user's perspective. Modern methods can improve the quality of existent soil information systems in three ways: updating, upgrading, and corroborating. In Chap. 18, Bedendo et al. present an approach to improve a physiography-based soil map in Entre-Ríos province, Argentina, using digital soil mapping techniques. Continuous productivity-index (PI) classes were predicted from a number of environmental covariates, mostly digital elevation model (DEM) derivatives, using regression and geostatistical techniques. The PI land classification was used to adjust the soil-landscape/soil-series interpretation of the existing choropleth soil map by correlating discrete PI values obtained from a conventional mapping procedure with continuous PI values obtained by digital soil mapping procedures.

Limited research has been carried out on the potential of microwave remote sensing data for spatial estimation of different topsoil properties, except for soil moisture. In Chap. 19, del Valle et al. intend to narrow down this knowledge gap by assessing the potential of ALOS PALSAR image mosaics for identifying and mapping land covers, as a cartographic base for soil mapping or as a value-added layer for integration of multi-source thematic data. The chapter also analyses changes in L-band backscatter overtime, and their relation to land degradation processes. To this end, a test area covering the north-eastern Patagonia region, Argentina, was chosen for its diversity of geology, geomorphology, soil, and land use, as well as for existing soil expertise and an ongoing regional soil-mapping project.

In Chap. 20, Farshad et al. compare two approaches to prepare photo-interpretation maps that guide the location of field observations and serve as frames for soil cartography. The physiographic approach is mainly descriptive and aims at separating relief units based on their physiognomic appearance. The geopedologic approach highlights relationships between soils and geoforms and aims at predicting patterns of soil distribution prior to field survey. Both approaches have been applied in the Henares river valley, Spain. The two interpretation maps are compared in terms of soil patterns and density of delineations.

Chapter 21 of Klingseisen et al. examines geopedology in the context of soil-landscape studies in Australia. It discusses two cases where GIS-based geomorphometric tools were used for semi-automated classification of landform elements, based on topographic attributes like slope, curvature, and elevation percentile. The case studies illustrate how results of the geomorphic classification add value to management decisions related to rangelands, precision agriculture, spatial analysis, modelling of land degradation, and other spatial modelling applications where landscape morphometry is an influential factor in environmental processes.

Geomorphometric analysis from digital elevation models (DEM) can contribute to improve information detail and accuracy and, thus, strengthen soil survey. This topic is discussed in Chap. 22 by Martínez and Correa. The approach was tested in a mountainous area of Colombia. Several geomorphometric parameters were calculated and a classification of landforms was created. The outputs can supplement existing soil studies and meet the information requirements of environmental spatial models, agricultural development, hydrological studies, land use and conservation.

The application of geomorphology to soil survey has encouraged the study of genetic relationships between soils and geoforms. In Chap. 23, Viloria and Pineda applied a quantitative method based on artificial neural network and fuzzy logic to classify the landscape into land-surface units from a digital elevation model (DEM). The classification output included a map showing the spatial distribution of land-surface classes. The method proved to be effective for establishing soil-landscape relationships in the study area.

33.5 Part IV: Applications in Land Degradation and Geohazard Studies

Environmental deterioration, land degradation, and geohazard are of increased concern in many regions around the world. In this regard, understanding and quantifying the geopedologic processes that such regions are undergoing are fundamental towards promoting efficient solutions. Part IV is dedicated to applications in land degradation and geohazard studies that use geomorphic and pedologic analysis integrating spatial modelling and earth observation information.

Chapter 24 of Bocco summarizes how gully erosion research has developed, its major achievements in the conceptual and methodological dimensions, and potential courses of action for further research, with emphasis on the contribution of geopedology. It is claimed that despite the advancements in the development of models and in remote sensing and GIS techniques, gully erosion remains a complex issue difficult to model and predict. In this regard, the author argues that geopedology may play a role in its understanding and management. As other geomorphic processes, gullies occur in certain terrain, soil, and hydrology conditions, which may be conveniently approached from a geopedologic perspective.

In Chap. 25, López Salgado discusses a qualitative causal model to assess susceptibility to mass movements using detailed geopedologic information. The approach was applied in a Colombian Andean watershed. Data were collected in sample areas and validated outside for mass movement hazard zoning. The results highlight the relationships between mass movement-promoting soil properties (mainly mechanical and physical) and resulting morphodynamic processes and features (mainly landslides, various solifluction forms, and terracettes). Soil properties were assessed in terms of their susceptibility to mass movements from an integrated soil-geomorphic map.

Knowledge of the soilscape, i.e. the pedologic portion of the landscape, its characteristics, and composition helps understand the relationships between causes, processes, and indicators of land degradation. Chapter 26 by Metternicht and Zinck describes the application of the geopedologic approach to map land degradation caused by soil salinity and predict salinization hazard in the semi-arid environment of the Cochabamba valleys in Bolivia. In addition of providing a framework to generate sub-regional soil information, geopedology assisted in understanding topsoil spectral reflectance features of soil degradation, assessing soil salinity type and magnitude, and predicting salinity hazard.

In Chap. 27, Sayago and Collantes report on significant land degradation in Tucumán province, Argentina, resulting from uncontrolled use of the Chaco ecosystem during the last centuries. Potential soil loss is mapped at small scale, based on geomorphic landscape sectorization and criteria of the Universal Soil Loss Equation (USLE). Models of land erosivity are developed in two scenarios of future climate change from extreme rainfall values recorded over the last century. The assessment of erosion hazard at small scale using USLE, remote sensing and GIS, helps develop programs oriented to the recovery of extensive degraded regions, through management systems adapted to current and future environmental conditions.

The geopedologic approach to soil mapping amplifies the role of geomorphology. It helps understand soil variation in the landscape, which increases mapping efficiency. In Chap. 28, Shrestha et al. show the adequacy of soil data resulting from geopedology-based predictive soil mapping for assessing land degradation in three locations of Thailand. The geopedologic approach helps map soil in inaccessible mountain areas, but for applications in land degradation studies all the required soil properties may not be available in a soil map. The effect of land cover and land use management practices on soil properties such as porosity and compaction having effect on hydraulic conductivity, a parameter used in modelling rainfall-runoff-soil erosion, is usually not reported in soil surveys. These data have to be collected separately. For mapping areas susceptible to frequent flood, the geomorphic understanding of the river valley dynamics and soil characterization help identify susceptible areas. Similarly, the study shows how the geopedologic approach in combination with digital image processing helps in mapping soil salinity hazard.

33.6 Part V: Applications in Land Use Planning and Land Zoning Studies

Part V is devoted to issues in land use planning and land zoning where geopedology plays a key role, both conceptually and in applied terms. These are important topics and are somehow neglected in the current scientific literature, more prone to purely digital mapping and pixel-based approaches. Semi-quantitative geopedologic studies aiming at the stratification of space for planning and zoning purposes are able to generate valuable scientific and practical information.

In Chap. 29, Escribano et al. determine zonation units geared towards balancing conservation and development in the Cabo de Gata-Níjar Natural Park, an arid region in south-eastern Spain. Ecosystems were identified selecting the attributes that exert the strongest influence on ecosystem dynamics at three nested spatial scales (ecosection, ecoserie, and ecotope). Geoform-soil and vegetation attributes provided the data needed to assess the conservation value and the vulnerability of the ecosystems to land use, crucial for the definition of a hierarchical zoning framework. The flexibility of the method allows analyzing the variables in different ways depending on the management objective. Furthermore, the use of meaningful score classes helps managers explain people the reasons behind land use restrictions, gaining their adhesion and minimizing social conflicts. This chapter fills a gap in conservation and development studies by characterizing ecosystems within a sound spatial framework. The approach is understandable by planners and other social actors lacking a thorough background in environmental studies; in addition it is solid and flexible, allowing for adaptive management purposes.

Silvicultural practices, including reforestation and afforestation are relevant to the provision of environmental services, to landscape rehabilitation, and in general to the sound conservation of natural resources, not only forests but also soils and water. One major challenge to these practices is the efficiency of the effort as measured in terms of successful plant viability and growth. In Chap. 30, Frugoni and Dezzoti show how geopedology has proven useful for assessing land suitability for pine plantation in north-western Patagonia, Argentina. The authors clearly indicate how silviculture requires valuable soilscape information at semi-detailed or detailed scale to assess suitability and monitor progress. Geopedologic maps provided spatial information on physical and chemical properties and terrain features. In spite of parent material homogeneity, soil-landscape relationships created variability in particular as related to water dynamics. In addition to supporting soil mapping, the approach served as a monitoring tool. Seven years after planting, ecological indicators related to plant diversity, forest regeneration, and soil protection showed improvement through project implementation. Lessons learned suggest that these variables should be carefully monitored so that the social, conservation, and economic objectives of the project can be sustainably achieved.

Land use planning and zoning frameworks are useful at all scales. However, area size (i.e. large, small) does not correlate with levels of difficulty associated to surveying and mapping. In fact, each scale offers challenges and solutions that can be addressed using geopedology. In Chap. 31, García describes a good example of territorial zoning at relatively low geographic resolutions (1:250,000 and 1:100,000 scales) in a fairly large fluvial basin in southern Venezuela, important in the provision of hydroelectricity at national level. The study is aimed at solving land management issues in the basin with the premise of long-term sustainability of power production. The study is strategic and involves far more than watershed management for suitable natural resource conservation. García proves that geopedology offers the backbone to these efforts. Territorial zoning of the catchment area, based on geomorphic and soil information, was undertaken as an initial step to propose land uses compatible with preserving the hydroelectric potential. Geomorphic units and their soil components, together with ancillary elements including the vegetation cover, were mapped at two scales using a multicategorial geoform classification system.

The zoning units were used for land evaluation and for establishing land use regulations required for the watershed management plan.

The closing chapter of Part V deals with land use planning in the western urban fringe of Caracas, the capital city of Venezuela. Urban fringes are special territories where understanding and managing social and natural processes in an integrated manner pose crucial challenges to settlers, politicians, planners, and administrators. Urban fringes in developing countries are dynamic areas that lack urban planning and usually harbor a majority of low income populations. In Chap. 32, Rodríguez and Zinck describe a framework for land use planning where land use conflict analysis represents an essential tool for decision making on land use allocation, taking into account the stakeholders interests. Resource inventory, especially geopedologic mapping, and land use conflict analysis generated basic input data for policy formulation and scenario building. The geoform classification system played a fundamental role in the delineation of basic map units serving as cartographic containers for the mapping of the other natural resources. A set of data items with different levels of aggregation was selected from the resource inventory and land evaluation, and used to rate the planning units.

33.7 Concluding Remarks

Geopedology is an approach to soil survey and other kinds of soil study. It combines pedologic and geomorphic criteria to establish soil map units in the practical-applied realm or analyze the relationships between soils and landscape evolution in the scientific realm. The geopedologic approach as described in Chap. 4 has been used primarily in soil mapping. In this context, geomorphology provides the contours of the map units ("the container"), while pedology provides the soil components of the map units ("the content"). Therefore, the units of the geopedologic map are more than soil units in the conventional sense of the term, since they also contain information about the geomorphic context in which soils have formed and are distributed. In this sense, the geopedologic unit is an approximate equivalent of the soilscape unit, but with the explicit indication that geomorphology is used to define the landscape. This is usually reflected in the map legend, which shows the geoforms as entries to the legend and their respective pedotaxa as descriptors.

Geopedology is mainly a conceptual framework, not a mapping technique in itself. It can be implemented with digital and convential survey techniques, apart or in combination, and using different survey norms and survey orders as shown in the various parts of the book. The geopedologic approach to soil survey and digital soil mapping are complementary, not mutually exclusive, and can be advantageously combined. The segmentation of the landscape sensu lato into geomorphic units provides spatial frames in which geostatistical and spectral analyses can be applied to assess detailed spatial variability of soils and geoforms, instead of blanket digital mapping over large territories. Geopedology provides information on the structure of the landscape in hierarchically organized geomorphic units, while digital techniques provide information extracted from remote-sensed imagery that help characterize the geomorphic units, mainly the morphographic and morphometric terrain surface features.

This book offers a set of examples that use different modalities or variants of geopedology from open soilscape approach for scientific research, to a more structured survey approach for mapping purposes. It shows the versatility and reach of geopedology thanks to the combination of pedology and geomorphology.