GEOGRAPHICAL INFORMATION SYSTEMS

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Introduction

The term 'geographic information system' (GIS) has become synonymous with a wide range of computer applications, technologies, and scientific methods related to the use of geospatial information. Although the origin of GIS can be traced back to early electronic mapping tools, such as the Canada Geographic Information System (CGIS) developed in the mid-1960s, limiting the definition of GIS to a spatial visualization tool would be to disregard its current scientific and technological standards, as well as the huge expansion of GIS applications in science, politics, and economics. Driven by the rapid growth of computer technologies on the one hand and globally increasing demands on spatial information on the other, GIS has evolved from an electronic mapping facility into a fast-growing spatial science technology in less than 40 years. Due to the amalgamation of computer-assisted cartography with database technologies and growing capabilities of analyzing data across different layers in an object-oriented programming environment, current GIS provides a universal management technology for capturing, analyzing, modeling, and displaying spatial data.

Apart from its technical dimension, the term GIS also describes an emerging methodical discipline which has become an established part of the curriculum, especially in geography. However, the close connection between geography and GIS is largely based on a chance semantic coincidence and less the result of methodical commitments to computer-based spatial analyses that took place during the so-called quantitative revolution of geography in the early 1970s. The evolution of GIS was fostered by the special applications, ideas, and GIS-based solutions of scientists, federal and national agencies, governmental departments, and commercial providers, as well as the huge user community. A multitude of alternative terms for GIS bear witness to the rapid spread of GIS technology, ranging from 'market-analysis information system' to 'image-based information system'. Since the early 1990s, these have included the term 'soil information system.'

Indeed, the notion of quantitative pedology, i.e., the modeling of soil formation as a function of state factors, initially seemed perfectly suited to the new GIS technology, especially since key functional features enabled overlay and modeling operations across apparently disparate spatial data sets. Although these optimistic assessments of 'intelligent technologies' soon had to be revised and, particularly in soil sciences, were followed by some disillusionment, mainly on account of the sheer complexity of soil, three GIS applications to soils have now become established. These take GIS back to its original purpose as a useful instrument in: (1) data inventory and management, (2) data analysis and mapping, and (3) modeling and decision support. Before discussing these in more detail, the following will summarize major GIS applications to soils to provide an overview of elementary features, basic principles, and methods of GIS.

Elementary Features and Basic Principles of GIS Applications to Soils

Basic principles of soil-related GIS applications are best shown using a three-step scheme of GIS evolution. Based on the long-standing development of the Canadian GIS family, with its strong commitment to environmental issues, the three-stage scheme is also appropriate for showing how soils are integrated into a GIS context within the above fields of application. A structured scheme, organized along a hierarchical sequence of activities and GIS applications, is given in **Figure 1**. Here, the assumption is of a research process ultimately targeted at supporting management decisions.

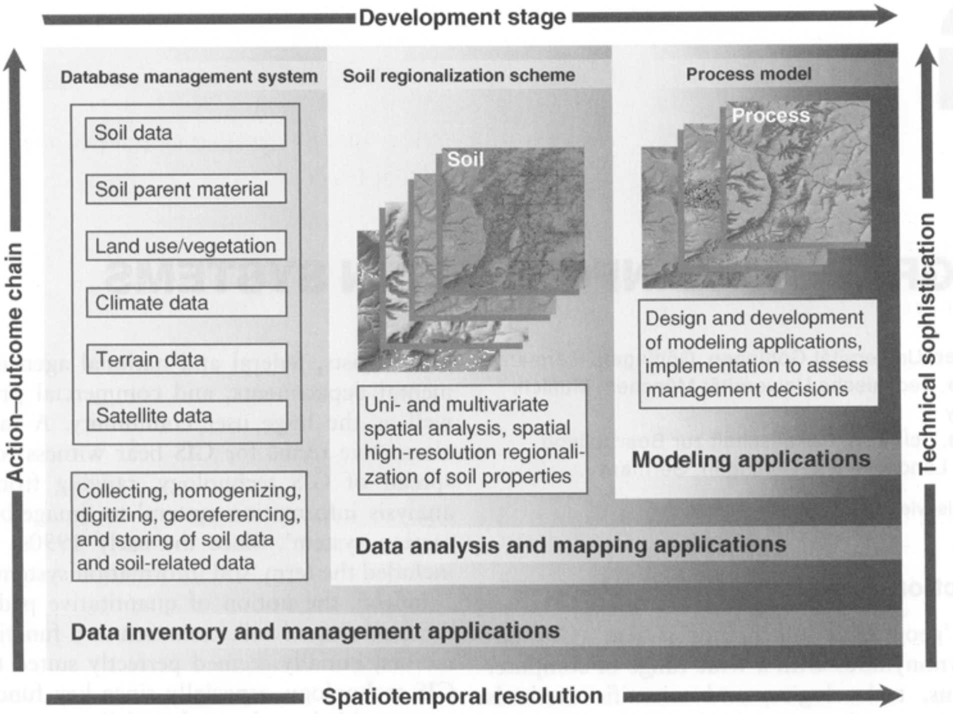

Figure 1 Conceptual model of the role of geographic information systems (GIS) and GIS applications to soils.

Taking the input data level as the essential and most crucial resource of a GIS, the initial phase of GIS evolution is characterized by data inventory and management applications. Assembling an appropriate database involves collecting, homogenizing, digitizing, georeferencing, and structured storing of data. In purely technical terms, the work consists of the design and implementation of a database management system suitable for fast data queries or searching. Although distinctions between soil and other intimately related environmental layers such as vegetation or climate are technically difficult, proper digital representation of soil and its three-dimensional variability above all requires different statistical data scales, ranging from nonquantitative nominal (e.g., soilscape) to metric entities (e.g., the organic matter content of a certain horizon). Since soils have in the past been entered into GIS as part of ambitious national or federal mapping programs that based their inventories on available soil maps, analogous soil maps have so far constituted a major data source. This leads to a distinct dominance of vector data representations, commonly consisting of discrete soil entities such as genetic soil types and local profile descriptions. Regularly spaced, continuous raster data representations of soil properties in contrast are still less common. Despite much progress in GIS-based data assembly and data management, digital maps and attribute tables therefore remain simple metaphors of the traditional soil map. The latter already represents a condensed and highly abstracted result of a knowledge-based research process, drawing on all the skills of soil scientists and cartographers at their current state of the art. Since all subsequent tasks and operations remain restricted by these academically essential but hardly operational issues, proper soil data representation demands at least some additional assembly of metadata information (e.g., site-specific descriptions of profile settings, scale issues, map conventions) if a solid scientific evaluation of all subsequent research results is to be enabled.

While inventory and management applications reflect the more technical dimension of GIS, the second stage of GIS evolution emphasizes data analysis and mapping applications. Since the term 'spatial analysis' includes a wide range of different methods that greatly vary in sophistication and complexity, a differentiation according to uni- and multivariate analysis to complement corresponding statistical methods is suggested. In this case, univariate spatial analyses would comprise all applications that analyze spatial (neighborhood) dependencies within one layer, e.g., autocorrelation, routing, or geostatistical analyses. Examples for soil-based applications include neighborhood analyses for delineating soil associations, or the geostatistical analyses frequently used to estimate a continuous metric soil layer (e.g., horizon depth) from random field data. The multivariate option could thus denote all kinds of analyses performed across different layers, leading to the production of a new spatial data set. This latter key functionality of a GIS is often utilized for soil regionalization purposes and will be discussed below in the Data analyses and mapping applications section. Although most current hybrid or extended GIS are capable of performing both kinds of spatial analyses using both vector and raster data, functionality and quality of analysis results still depend on which data model is used and reflect the former preferences and roots of software packages. Particularly in soil science, where spatial analyses and mapping are based on two differing views of soil, either regarding it as a spatially discrete genetic entity or a composition of spatially continuous layers, a GIS software package still needs to be chosen in accordance with the type of spatial analyses to be carried out.

In the third and most developed phase of GIS, modeling and decision-support applications are emphasized. This results from the user's desire to understand spatial patterns and processes or to undertake more complex modeling operations, required for instance to assess objectively environmental management or political decisions. Due to increasing computing capacities and advanced object-oriented programming environments, current GIS provides sufficient modeling capabilities to render this most prominent application of GIS. This in turn substantiates the use and view of GIS as a decision-support system. While soil still forms the actual research object or predictant variable in GIS-based analysis and mapping, the modeling stage integrates soil and its closely related environmental layers as predictor variables. Their aim is to model more complex climatic processes or to run scenarios of land use change in an attempt to predict the effects of management decisions.

Throughout these stages of GIS development, soils evolve from a rather static object of inventory to an essential, highly dynamic, reactive and controlling subject. In view of the spatial resolution required by certain applications, large-scale inventories satisfactory for purposes of national or federal information are replaced by a high-resolution regionalization of soil properties capable of supporting complex modeling applications. The importance of GIS also changes; it is best described as a transition process, beginning with its use as a transaction-processing system and technical tool for data management. GIS then goes on to become an array of scientific analytical methods capable of supporting the basic demands of spatial information science, with the final stage as a decision-support system, with potential uses within a range of applications.

Data Inventory and Management Applications

In view of society's growing demands for environmental services, a huge number of international, national, and federal inventory and mapping programs have been set up from the early pioneering stage of GIS in the 1960s. Initially conceived against the urgent need for increased agricultural production, more recent aims include the maintenance and qualitative enhancement of natural and rural (agro-)environments. Due to the dual role of soil as a production factor and an interacting and controlling layer within the atmosphere–biosphere–geosphere system, the assemblage of soil data was of particular interest in the context of developing ambitious agroenvironmental instruments capable of supporting sustainable development. The momentum of this development is reflected in an increasing number of soil information systems. Although they are mostly embedded in primary land or environment information systems, they distinctly show the technical and scientific specialization required for handling and providing digital soil and soil-related information.

On a global scale, the broad-resolution *Digital Soil Map of the World* (DSMW), a digital derivative of the Food and Agriculture Organization of the United Nations (FAO/UNESCO) soil map of the world, is considered the most detailed, globally consistent soil data set. The original 1 : 5 000 000 map represents a generalization of more detailed data derived from about 11 000 soil maps reviewed from various countries, which vary widely in reliability, detail, precision, scales, and methodologies. In line with the analogous source, both vector- (scale 1 : 5 000 000) and raster (spacing 5 × 5 arc min)-based derivatives include soil types, texture, profile depth, and surface slopes, as well as derived soil properties provided by interpretation programs and related data files on agronomic and environmental parameters. Apart from the maps of classification units contained in the *World Soil Reference Base* (WSRB) and tables on special soil analyses for every country of the world, an additional soil database was created for global environmental studies, including data on soil-moisture storage capacity, soil-drainage classes, and effective soil depth. A corresponding data set of water-holding capacities in a 1° × 1° grid (latitude, longitude), drawn from original sources to meet the requirements of general circulation model (GCM) experiments, can be quoted as another example of using soil data in the context of global environmental studies.

Despite its broad spatial resolution and distinctly limited information content, features that are unlikely to be improved by the current SOTER revision (soil and terrain database of the world), the compilation of the global soil map and its digital derivative did contribute much to academic debates on the global harmonization of soil classification concepts and may also have influenced the development of many continental, national, and federal soil information systems. Prominent examples of well-established projects, such as the National Soil Information System in the USA (NASIS), the Canadian Soil Information System (CanSIS), the Australian Soil Resource Information System (ASRIS), or the European Soil Information System (EUSIS), form a suitable basis for a steady, coordinated, and harmonized inventory of soil and soil-related data in accordance with essential environmental tasks. Indeed, precise manuals of procedure setting out requirements, inherent concepts, and methods essential for a rationalized inventory of georeferenced, digital soil databases have given rise to an increasing availability of plausible and consistent soil data accessible for many purposes.

Using the ambitious EUSIS project as an example, **Figure 2** shows the construction of a soil information system database. The relational structure consists of topological, semantic, and geometric data sets, organized along a hierarchical chain of discrete soil entities (objects). The topological tables contain information on the distribution of soil bodies within soilscapes and soil horizons within soil bodies (organization tables), as well as information on the nature of limits, separating different soil-scapes within a soil region (limits table). The properties of soils, mostly attached to soil bodies and horizons, are given in the semantic attribute data sets, whereas positions and shapes are captured by the geometric-attribute data sets. To address the needs of soil information users at different scales, EUSIS is organized along a scale-dependent structure. Spatial soil information is assembled and provided at global 1 : 5 000 000 scales compatible with the SOTER database of the FAO, at intermediate 1 : 1 000 000 scales covered by the *Soil Geographical Database of Europe* (SGDBE) and at 1 : 250 000 scales. Larger scales (1 : 50 000, 1 : 5 000) are covered by regional to local authorities. To ensure homogenous data contribution and assembly, EUSIS partly links up with existing national and federal soil information systems (e.g., Lower Saxony Soil Information System, NIBIS, Germany). Special working groups in the European Soil Bureau (1 : 1 000 000, European Soil Database working group; 1 : 250 000, working group) coordinate data contribution and management in accordance with the relevant scales.

Despite clear differences between individual soil information systems, particularly in terms of subdividing soil categories and the match between soil taxonomy and soil map units, most systems reflect the EUSIS structure and are conceptualized along traditional map scale conventions. Since the genetic soil category or soil type, although somewhat modified, is still employed as the major response unit, the common practice of direct, rule-based delineation of pedotransfer functions from these discrete entities yields no more than a coarse estimate, with clear limitations in terms of spatial distribution, resolution,

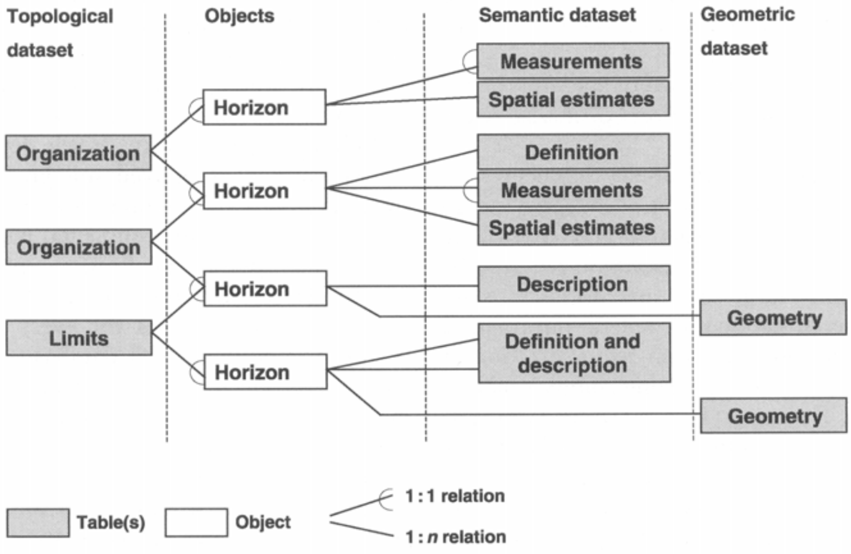

Figure 2 General structure of the European Soil Information System (EUSIS) database.

and reliability. Though soil information systems technology stresses its developments by catchwords such as 'multiuser access' or 'just-in-time performance,' its continued focus on discrete mapping units may well satisfy classification and pedogenetic criteria but does not necessarily meet the needs of prospective uses. Despite the global increase in reliable soil data, the current global soil inventory is not in a position to meet the increasing demands posed by soil protection, sustainable soil management, or other major political issues. These ambitious aims demand a spatially flexible database of different soil properties, which may be obtained through further GIS analyses.

Data Analyses and Mapping Applications

GIS-based data analyses and mapping operations have been widely developed for the purpose of yielding high spatial-resolution estimates of different soil properties. Apart from univariate interpolation techniques performed on random field data, for example, multivariate regionalization approaches in quantitative soil pattern analyses are the most frequently used, describing the spatial variability of soils in terms of a set of determining predictant variables and thus providing insight into the processes and factors involved. The term 'regionalization' is preferred in this context, since it comprises the somewhat misleading terms of 'upscaling,' 'downscaling,' 'interpolation,' and 'extrapolation' and also covers the major contemporary approaches of soil-mapping support, roughly to be divided into a predominantly vector-based approach and a continuous raster-based approach.

The knowledge-based discrete approach (or concept map approach) is still the most frequently used instrument of support in soil mapping. In accordance with Jenny's factorial theory of pedogenesis, a set of state factors such as, e.g., parent material, terrain, climate, or vegetation is statistically compared with the spatial soil pattern by utilizing overlay and intersection algorithms as key functional operations of GIS. The smallest common geometries of state factors are identified as a surrogate for the site-specific process structure, to enable a rule-based assignment of soil parameters and infer estimations of spatial soil patterns with a certain probability. Since state factors within a landscape system are intimately related, a landscape component can thus be assigned to typical patterns of landform elements, soil types, or vegetation sequences at each level of the spatial hierarchy. Adequate capture of covariance structures allows data gaps to be filled (e.g., in the ASRIS project performed on the basis of adjacent, properly mapped soil distributions), or infers spatial soil pattern at finer resolutions commensurate with terrain or vegetation information. By integrating sophisticated complex analytical methods such as fuzzy logic or the use of neuronal nets, characterized by their reduced reliance on expert knowledge in computing concept maps, descriptive rule-based models and expert systems can yield many supporting features of an improved and extended spatial definition of soil patterns. However, the discrete approach has distinct limits, particularly resulting from the finite number of predictant entities which may neither represent the spatial soil diversity in the area concerned nor the process scopes relevant to soil. Also, the classification of continuous, process-controlling geofactors (e.g., climate, relief) represents a critical task, since it involves an a priori assumption that the limits inferred are actually relevant for the distribution of soil characteristics and its spatial definition.

In view of these deficiencies, the continuous soil regionalization approach is sometimes preferred, particularly where metric soil properties are required for further use, e.g., in process models. Based on the definition of soil as a composition of continuous layers, a set of continuous terrain parameters has been used as predictor variables in the context of using statistical and geostatistical procedures for inferring spatial soil estimates from metric point data. Results indicate significant correlations between soil and terrain variables, particularly when complex, hydrologically based terrain indices, such as the Terrain Wetness Index (TWI; see **Figure** 3) are analyzed. Other results confirm that much of the variation apparent in soil is a response to near-ground runoff and associated translocation processes. To ensure consistent applicability of a continuous regionalization scheme to other climatic regions, recent applications have extended the continuous approach by integrating spatial high-resolution climate and terrain variables to complex process parameters. **Figure 3** exemplifies the Mass Balance Index (MBI) for the parameterization of slope transfer processes, integrating the universal soil-loss equation (USLE) *R*-factor and different catchment area parameters (catchment area, catchment slope). Since terrain parameters based on nonlinear discharge models tend toward strongly artificial variability, particularly in hydrologic homogenous areas (e.g., large valley grounds), the SAGA (system for an automated geoscientific analysis) Terrain Wetness Index (STWI) applies a slope-dependent, iterative modification scheme to the catchment area size (**Figure** 3) which keeps it suitable for the regionalization of hydromorphic soil properties. Different statistical and geostatistical regionalization methods performed on a set of terrain and process parameters were evaluated with regard to their routine application in the context of soil mapping. Universal kriging

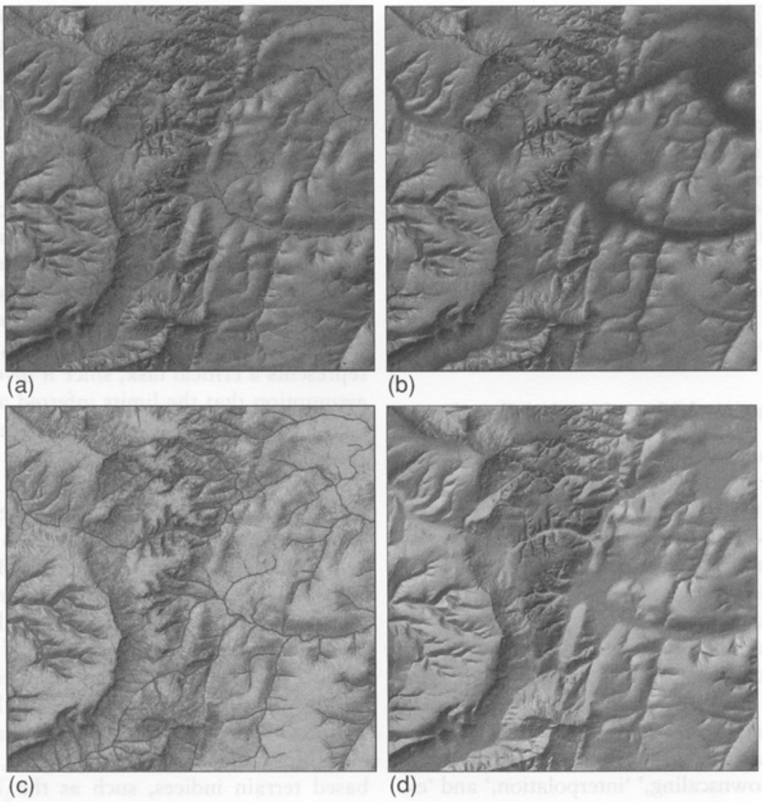

Figure 3 (see color plate 29) (a) Terrain wetness index. (According to Moore ID, Gessler PE, and Peterson GA (1993) Soil attribute prediction using terrain analysis. *Soil Science Society of America Journal* 57: 443–452); (b) SAGA (system for an automated geoscientific analysis) terrain wetness index; (c) mass balance index; and (d) silt content of the soil surface layer (red, high silt content; green, low silt content). (Adapted from Böhner J, Köthe R, Conrad O *et al.* (2003) Soil regionalization by means of terrain analysis and process parameterization. In: Micheli E, Nachtergaele F, and Montanarella L (eds) *Contributions to the International Symposium Soil Classification 2001*, Ispra, Italy. EUR 20398 EN. European Soil Bureau, Joint Research Centre.)

was assessed as a valuable tool for soil mapping and further modeling support. Results are exemplified for the regionalization of the topsoil silt content obtained by universal kriging (Figure 3). The strong emphasis on process throughout the regionalization scheme reflects the basic assumption that no matter which strategy is used for soil regionalization, a reliable spatial prognosis of soil properties can only be achieved if the underlying spatial data directly represent soil-related processes rather than being substituted by discrete factor combinations. Distinct limits in applicability, often the main focus of criticism, are due to the comparably high demands on soil measurements or profile data. In view of the growing availability of very-high-resolution remote sensing and particularly radar data, capable, for example of picturing topsoil moisture distribution and thus topsoil subscale (random) variability, this difficulty is likely to be overcome in the medium term. Nevertheless, a proper point database remains an essential basis for continuous soil regionalization.

Modeling and Decision-Support applications

Since the above soil regionalization approaches empirically detect predictable set structures within spatial soil variations and are thus occasionally termed 'models' themselves, this term is really reserved for the type of process modeling applications described below. The integration of soil as a reacting and controlling body into process models expands the capabilities of quantitative, GIS-based simulation, with ensuing benefits to a range of applications, particularly in the context of management decision support. Apart from hydrologic models, with their specific demands on horizontal and vertical soil data distribution, a wide range of applications exist in the context of soil erosion risk assessments. They can roughly be divided into empirical and physical approaches, with both requiring pedophysical values or at least a parameterization of certain soil properties.

Possibly the most prominent approach for estimating water-induced soil erosion, the USLE, is now predominantly carried out on a GIS basis on account of its comparatively simple structure. The USLE consists of an empirical equation which calculates the mean annual soil-erosion rates on agricultural slopes as a function of six variables (R, precipitation factor; L, slope length factor; S, slope factor; C, vegetation cover and tillage factor; K, soil-erodibility factor; P, erosion-protection factor). The parameterization of the topsoil erodibility in the K-factor considers soil particle size distributions (sand and silt percentages), organic matter content, and classes of permeability of the soil surface layer, e.g., entailed or delineated from soil taxonomy profiles. Comparable demands on the parameterization of topsoil properties are also valid for the empirically based wind-erosion equation (WEQ), predicting the potential mean annual soil loss at the field scale by determining the influence of several primary variables characterizing soil erodibility, wind erosivity, and the actual land-use situation.

Due to the limited transferability of empirically based erosion risk assessments, more sophisticated, process-based approaches have recently been developed capable of simulating water and wind erosion in a physically consistent manner. Their major advantage of wide applicability is countered by the disadvantage of extended data requirements on the spatiotemporal resolution and the quality of input parameters. This is particularly valid for soil data, which

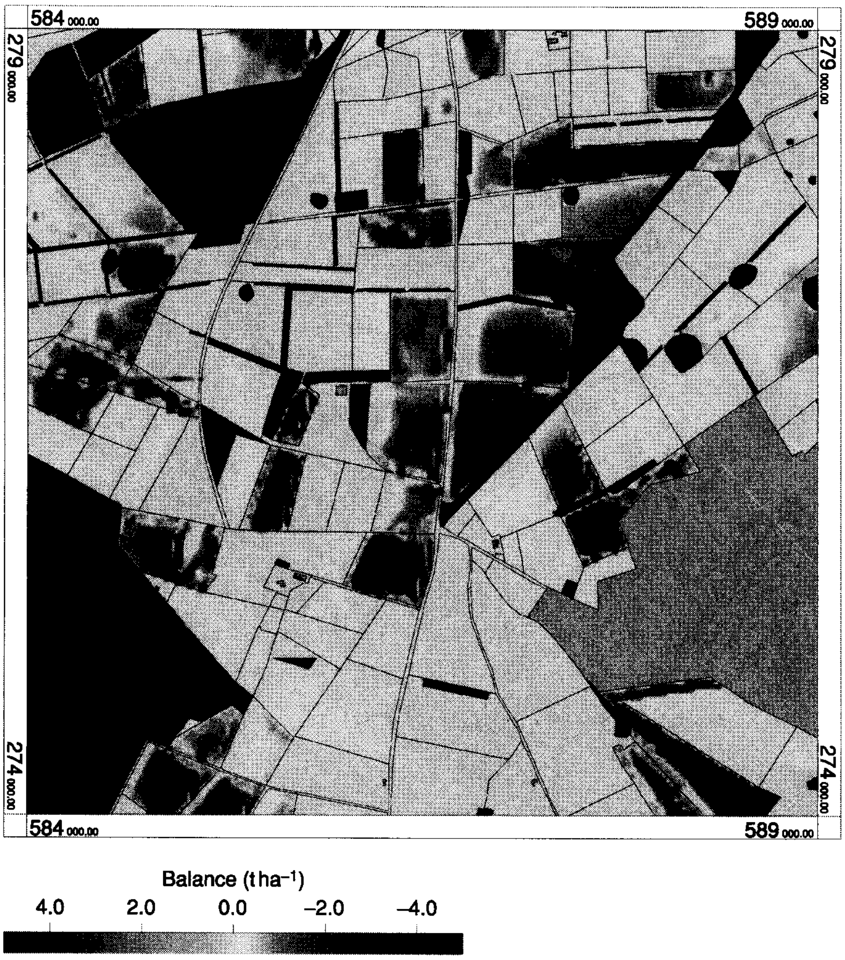

Figure 4 (see color plate 30) Spatial distribution of the erosion–accumulation balance for the event of 13 and 14 March 1994 at the Barnham test site, UK. Positive values (green) indicate accumulation; negative values (yellow and red) indicate erosion (dark green, forests; gray, settlements and Honington airport). Average wind direction of the storm was west (240–300° direction angle). Model domain covers 5 × 5 km. Reproduced from Bohner *et al.* (2003) The Weels model: methods, results and limitations. *Catena* 52: 289–308, with permission from Elsevier.

have to be available either as physical soil attributes or as delineated parameterizations. With respect to its prospective use in case studies, management decision support, and particularly in context with precision farming applications, major requirements concern the spatial resolution and thus demand a suitable procedure for the regionalization of metric topsoil properties.

Emphasizing this, **Figures** 4 and 5 exemplify the results of physically based wind-erosion simulations using the wind erosion on European light soils (WEELS) model, performed on spatial high-resolution estimations of soil particle distribution and surface-layer organic matter content. Apart from the soil-erodibility factor, soil attributes are essential inputs for the temporal high-resolution simulation of topsoil moisture contents, since they essentially determine the process of wind erosion. The WEELS model also considers various climatic parameters, annual changes in land use, crop cycles, and crop phenology, as well as the influence of the terrain. Due to its high temporal resolution (hourly) the WEELS model allows the simulation of wind-erosion events (**Figure** 4 shows an event at the Barnham test site, UK) as well as long-term estimates of erosion and accumulation rates. The spatial distribution of erosion and accumulation rates for the Barnham test site (**Figure** 5) was derived from a 29-year model run (1970–98). The option of long-term simulations enables the assessment of different land-management scenarios and their susceptibility to wind-erosion processes. The result of land-use change scenarios for a test area in Grönheim in the Cloppenburg Geest area (the western part of Lower Saxony) has shown the possibility of minimizing erosion risks through sustainable land-use strategies. This can underline the capabilities of GIS-based modeling and decision support in the context of environmental policy and management.

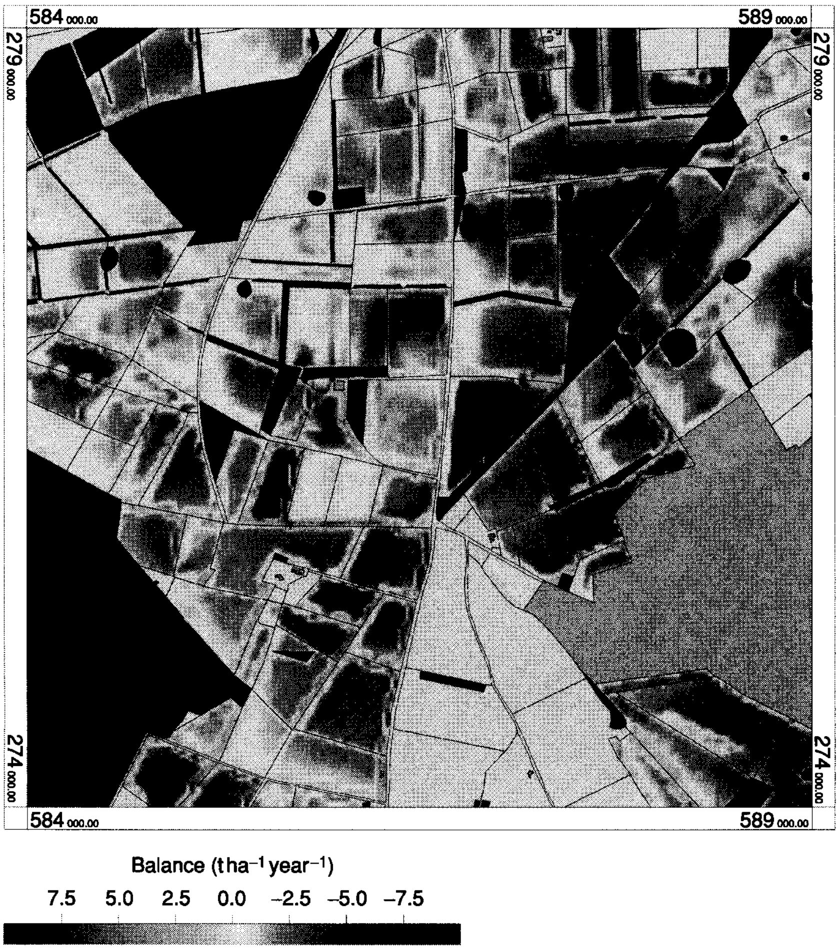

Figure 5 (see color plate 31) Modeled spatial distribution of the mean annual erosion–accumulation balance at the Barnham test site, UK (1970–98). Due to changing wind directions and annually varying vegetation cover, the orientation of the soil erosion rate gradient may differ among the individual fields (dark green, forests; gray, settlements and Honington airport). Model domain covers 5 × 5 km. Reproduced from Bohner *et al.* (2003) The Weels model: methods, results and limitations. *Catena* 52: 289–308, with permission from Elsevier.

Summary

The evolution of GIS in terms of technical maturity and functionality offers many possibilities for application to soils, ranging from data assembly and inventory support to complex modeling. The proliferation of GIS within the scientific community has fostered its frequent use in spatial data analyses, particularly in the context of soil-mapping support and soil regionalization. Due to their increasing ability to analyze data across different layers, GIS constitute suitable instruments for developing soil-related process models with wide potential applications for instance in decision-support systems. However, the clear technical advantages cannot detract from the fact that the most crucial resource of a GIS, the database itself, still tends to be a digital derivative of a traditional soil map. It therefore comprises individual scientific field experience as well as mapping conventions, neither of which can be easily reproduced in a digital format. The persistance of the genetically well-founded, discrete soil entity as the basic information unit and particularly the direct delineation of (coarse estimated) pedotransfer functions is hardly capable of meeting the increasing demands for soil information in terms of spatial resolution and reliability, and thus to a certain extent even violates the capabilities of current GIS. A major alternative, the spatial high-resolution regionalization of available soil profile data – an alternative which would deliver more-reliable soil estimates despite its being transcribed from an older classification system – above all requires an appropriate soil profile database. Though soil profile data are often compiled as part of developing national or international soil information systems, a systematic compilation and homogenization of available profile data on a national or international level is currently unavailable. This is therefore suggested as one of the most important future tasks in the further development of national and international soil information systems. Clearly this is no easy feat, but a rewarding task in view of the expected increase in knowledge on soil-formation processes. Rather than GIS users, it will, however, require GIS-using soil scientists.

See also: **Environmental Monitoring**; **Erosion:** Water-Induced; Wind-Induced; **Remote Sensing:** Organic Matter; **Spatial Variation, Soil Properties**; **Statistics in Soil Science**

Further Reading

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