New Trends in Soil Micromorphology

Selim Kapur · Ahmet Mermut ·
Georges Stoops (Eds.)

New Trends in Soil Micromorphology

Springer

Selim Kapur
University of Cukorova
Department of Soil and Archaeometry
Adana
Turkey

Dr. Ahmet Mermut
University of Saskatchewan
Dept. Soil Science
Saskatoon SK S7N 5A8
Canada

Prof. Dr. Georges Stoops
Ghent University
Dept. Geology & Soil Sciences
Krijgslaan 281 S8
9000 Gent
Belgium

ISBN: 978-3-540-79133-1 e-ISBN: 978-3-540-79134-8

Library of Congress Control Number: 2008932572

Cover design: deblik, Berlin

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

Contents

List of Contributors

Hema Achyuthan
Department of Geology, Anna University, Chennai 600 025, India,
e-mail: hachyuthan@yahoo.com

Montserrat Antúnez
Department of Environment and Soil Sciences, University of Lleida Av. Rovira
Roure 191, 25198 Lleida, Catalonia

O. Arnalds
Agricultural University of Iceland, Reykjavik, Iceland

J. M. Arocena
College of Science and Management; Canada Research Chair – Soil and
Environmental Sciences University of Northern British Columbia 3333 University
Way, Prince George, BC Canada V2N 4Z9, e-mail: arocenaj@unbc.ca

S. Blok
Institute for Biodiversity and Ecosystem Dynamics (IBED), University of
Amsterdam, Nieuwe Achtergracht 166, 1024 AD Amsterdam, The Netherlands

W.E.H. Blum
Institute of Soil Research, Department of Forest and Soil Sciences, University of
Natural Resources and Applied Life Sciences (BOKU), Vienna, Austria,
e-mail: herma.exner@boku.ac.at

Jaume Boixadera
Department of Environment and Soil Sciences, University of Lleida Av. Rovira
Roure 191, 25198 Lleida, Catalonia; Secció d'Avaluació de Recursos Agraris,
DARP, Generalitat de Catalunya

Z. Chen
Environmental Monitoring and Evaluation Branch Alberta Environment, 9820-106
Street, Edmonton, AB CANADA T5K 2J6, e-mail: Chi.Chen@gov.ab.ca

Marie-Agnès Courty
UMR 5198, CNRS-IPH, Centre Européen de Recherches Préhistoriques,
Avenue Léon-Jean Grégory, 66720 Tautavel, France,
e-mail: courty@tautavel.univ-perp.fr

Alex Crisci
CMTC INP, 1260 rue de la Piscine, BP 75, 38402 Saint Martin d'Hères, France,
e-mail: alexandre.crisci@cmtc.inpg.fr

María de Lourdes Flores-Delgadillo
Departamento de Edafología, Instituto de Geología, UNAM

Scott L. Fedick
Department of Anthropology, University of California, Riverside,
e-mail: scott.fedick@ucr.edu

Michel Fedoroff
Laboratoriy Electrochimie & Chimie analytique, ENSCP, 11 rue Pierre et Marie
Curie, 75231 Paris, France, e-mail: michel-fedoroff@enscp.jussieur.fr

N. Fedoroff
Institut National Agronomique, 78850 Thiverval-Grignon, France,
e-mail: nicolas.fedoroff@wanadoo.fr

T. S. Gendler
Institute of Physics of the Earth, Russian Academy of Sciences, Bolshaya
Gruzinskaya 10, Moscow 123810, Russia, e-mail: gendler06@mail.ru

M. Gérard
UR GEOTROPE, Institut de Recherche pour le Développement, Bondy, France

Paul Greenwood
Centre for Land Rehabilitation, School of Earth and Geographical Sciences
University of WA, 35 Stirling Hwy, Crawley, 6009, Australia,
e-mail: Paul.Greenwood@uwa.edu.au

Kliti Grice
Department of Applied Chemistry, Curtin University of Technology, GPO Box
1987, 6845 Perth, Australia, e-mail: K.Grice@curtin.edu.au

A. Heidari
Department of Soil Science, Agriculture College, University of Tehran,
Daneshkadeh St. Karaj, Iran, e-mail: aheidari82@yahoo.com,

F. Heller
Institut für Geophysik, ETH Hönggerberg, CH-8093 Zürich, Switzerland,
e-mail: heller@mag.ig.erdw.ethz.ch

G.S. Humphreys
Department of Physical Geography, School of Environmental and Life Sciences,
Macquarie University, NSW, Australia

Tang Keli
Institute of Soil and Water Conservation, CAS, Yangling, Shaanxi 712100,
China, e-mail: kltang@ms.iswc.ac.cn

Miroslav Kutílek
Emeritus Professor, Nad Patankou 34, 160 00 Prague 6, Czech Rep.,
e-mail: miroslav.kutilek@volny.cz

Hua Lizhong
Institute of Mountain Hazards and Environment, CAS, Chengdu, Sichuan 610041;
Graduate University of Chinese Academy of Science, Beijing 100039,
China, e-mail: hualizhong2008@yahoo.com.cn

S. Mahmoodi
Department of Soil Science, Agriculture College, University of Tehran,
Daneshkadeh St. Karaj, Tran, e-mail: smahmodi@chamran.ut.ac.ir,

Maria Gerasimova
Moscow Lomonosov University, Faculty of Geography Leninskie Gory 119992,
Russia, e-mail: etingof@glasnet.ru

Marina Lebedeva
Dokuchaev Soil Science Institute, Pyzhevskiy pereulok, 7, Moscow 109017,
Russia, e-mail: etingof@glasnet.ru

Michel Mermoux
LEPMI-ENSEEG, Domaine Universitaire, BP75, 38042 Saint-Martin d’Hères,
France, e-mail: Michel.Mermoux@enseeg.inpg.fr

Marcello Pagliai
CRA – Centro di ricerca per l’agrobiologia e la pedologia, Piazza M. D’Azeglio
30–50121 Firenze, Italy, e-mail: marcello.pagliai@entecra.it

Teresa Pi-Puig
Departamento de Geoquímica, Instituto de Geología, UNAM,
e-mail: tpuig@geologia.unam.mx

Rosa Maria Poch
Department of Environment and Soil Sciences, University of Lleida Av. Rovira
Roure 191, 25198 Lleida, Catalonia, e-mail: rosa.poch@macs.udl.cat

P. Sanborn
Ecosystem Science and Management, University of Northern British Columbia,
3333 University Way, Prince George, BC Canada V2N4Z9, e-mail: sanborn@unbc.ca

David Smith
Lab. LEME/Nanoanalysis, MNHN, Laboratoire de Minéralogie, 61 rue Buffon,
75005 Paris, France, e-mail: davsmith@mnhn.fr

Sergey Sedov
Departamento de Edafología, Instituto de Geología, UNAM,
e-mail: sergey@geologia.unam.mx

Elizabeth Solleiro-Rebolledo
Departamento de Edafología, Instituto de Geología, UNAM,
e-mail: solleiro@geologi a.unam.mx

G. Stoops
Laboratorium voor Mineralogie, Petrologie en Micropedologie, Universiteit Gent;
Department of Geology and Soil Science, Ghent University, Krijgslaan 281, S8,
B-9000 Ghent, Belgium, e-mail: georges.stoops@ugent.be,

Mark Thiemens
Department of Chemistry and Biochemistry, University of California, San Diego
92093-0352, USA, e-mail: mht@chem.ucsd.edu

A. Tsatskin
Zinman Institute of Archaeology, University of Haifa, Haifa 31905, Israel,
e-mail: tsatskin@research.haifa.ac.il

Ernestina Vallejo-Gómez
Departamento de Edafología, Instituto de Geología, UNAM

J. van Mourik
Institute for Biodiversity and Ecosystem Dynamics (IBED), University of
Amsterdam. Nieuwe Achtergracht 166, 1024 AD Amsterdam

P. G. Walsh
Department of Physical Geography, School of Environmental and Life Sciences,
Macquarie University; Forests NSW, Department of Primary Industries, NSW,
Australia, e-mail: peterwa@sf.nsw.gov.au

He Xiubin
Institute of Mountain Hazards and Environment, CAS, Chengdu, Sichuan 610041;
Institute of Soil and Water Conservation, CAS, Yangling, Shaanxi 712100, China,
e-mail: xiubinh@imde.ac.cn

Bao Yuhai
Institute of Mountain Hazards and Environment, CAS, Chengdu, Sichuan 610041;
Graduate University of Chinese Academy of Science, Beijing 100039,
China, e-mail: byhcw@126.com

Geoffrey Steel Humphreys 1953–2007

Geoff Humphreys died suddenly and unexpectedly in Sydney on August 12th, 2007, tragically early at 54 but surrounded by the bush he loved so much. As recently as two days before his death, Geoff was in the field having a great time being outdoors, digging holes, talking about his research and engaging with people interested in understanding how landscapes function. Geoff's interest in the formation of soil and its management, and his breadth of experience and interests, brought him into contact with many in the geomorphological, Quaternary and ecological communities.

Geoff enrolled at Macquarie University as an undergraduate in the early 1970s initially studying economics but soon transferring to the earth sciences where his real interests lay. He took full advantage of the flexibility Macquarie offered by studying a mix of geography, geology and biology. He graduated with first class Honours in 1977 and was encouraged to move directly onto a PhD. Although Geoff worked in a range of different areas, what he regarded as the core of his research was his work on bioturbation of soils. He started this work in his honours research in 1975/76 when he began investigating the effects of ants, termites, worms and insects on podsol soils around Sydney. Geoff expanded this into the topic of his PhD research: how soil-dwelling organisms affect the formation of soils (specifically texture-contrast soils, typical of hillslopes around Sydney). The subject arose at the suggestion of Ron Paton, his supervisor, but Geoff insisted on adopting a quantitative approach. Geoff knew that to convince people of the importance of these small animals he would need to measure volumes, areas, rates and depths so that there could be no argument about their significance in soil formation. In this Geoff succeeded: the quantitative work forms the backbone of both journal papers and the bioturbation chapter in 'Soils: a new global view' which is still some of the best work published on the topic. This multi-disciplinary approach stayed with

Geoff throughout his career as he devised new ways of understanding the role of the biosphere in soil formation.

Geoff met his wife Janelle at Macquarie and together they moved to Papua New Guinea in 1979, first in Chimbu Province in the Highlands and later at the University of Papua New Guinea from 1983 to 1987. Geoff worked on his PhD as a student of Macquarie University before and during his time in PNG, somehow managing to work up the Sydney-based field data while living in PNG, teaching at the University of Papua New Guinea and raising a family. After graduating in 1985, Geoff took up a position at the University of New South Wales in 1987 and then, in 1989, an appointment in the Land Management Project in the Research School of Pacific Studies at ANU which saw him return to PNG and also to other parts of Asia and the Pacific and even Africa for long field seasons. Geoff was fascinated by the spectacular and highly dynamic landscapes of these countries, which he investigated with boundless enthusiasm.

Geoff began lecturing at Macquarie University in mid-1994 just as he and his Macquarie colleagues Ron Paton and Peter Mitchell were completing their book 'Soils: A new global view'. One of Geoff's proudest achievements was to be awarded (with his co-authors) the G.K. Gilbert Award for excellence in geomorphological research by the Geomorphology Specialty Group of the Association of American Geographers in March 1999 for this book and for the impact the book created. In an article titled *Shock the World (and then some)*, Randall Schaetzl included it within the four most groundbreaking and influential treatises on geomorphology and pedology of the 20th Century. Other reviewers put the book at the front of a paradigm shift in the understanding of soil genesis, although it is fair to say that views were wide-ranging. He was sometimes frustrated by the entrenched and intransigent positions within pedology. Partly as a response, and partly just recognising a good scientific opportunity, in recent years Geoff in collaboration with others, was very innovative in bending new techniques in earth sciences to his task of measuring soil processes including single-grain optically stimulated luminescence dating to measure soil turnover rates, terrestrial cosmogenic nuclides to measure rates of soil production (conversion of rock to soil) and, uranium series disequilibrium methods to measure soil formation age. In addition to those innovative directions, he continued to collaborate with Ron Paton on soil genesis issues right up to his death, with two papers critically evaluating the zonalistic foundations of soil science in the USA published in *Geoderma* in 2007.

Geoff was a highly respected and valued member of the soil science community in Australia and around the world. Geoff was instrumental in the establishment of the Soil Morphology and Micromorphology Commission of the IUSS, which he chaired from 2002 to 2006 and at the time of his death was 2nd Vice Chair. In this role he is said to have breathed new life into the morphological study of soils. He was active in ASSSI (Australian Soil Science Society Inc), representing the NSW Branch on the organising Committee of the Brisbane 2010 World Congress.

In addition to his fine research contributions, Geoff will be remembered as a great teacher and advocate of soil science and scientific research in general. As an Associate Dean of Research at Macquarie University, he was an energetic contributor on several post graduate and research guiding committees. For 11 years he was co-editor of the Australian Geographer.

In his time at Macquarie Geoff revelled in the supervision of many students in a range of subjects. Somewhere in each of those projects were a link back to understanding how soils form and an original and imaginative approach to tackling intractable problems. Along the way he made important contributions to studies of soil erosion and land degradation, ecology, geomorphology and the Quaternary.

Geoff recognised the critical importance of detailed quantitative observations of soil morphology at the macro and micro scales. In collaboration with others in Australia and internationally, he sought to unlock secrets of pedology revealed by soil morphological features, generating an impressive publication output along the way. More generally, Geoff has been credited with paving the way for a truly modern, interdisciplinary approach to pedology, one that effectively incorporates geomorphological and ecological principles, and this is perhaps the primary legacy of Geoff's career.

The outpouring of sadness at the news of his death was the greatest demonstration of the warmth with which Geoff was regarded by hundreds of friends, colleagues and students, past and present. Geoff will be greatly missed by his many friends, colleagues (past and present) and former students as well as his family: Janelle, Sheridan, Lachlan, Rowan, William and grandson Max.

Paul Hesse, Jonathan Gray and others

The Role of Soil Micromorphology in the Light of the European Thematic Strategy for Soil Protection

W. E. H. Blum

Abstract The role of soil micromorphology within new soil research concepts developed for the European Thematic Strategy for Soil Protection is explained. Soil micromorphology has a central function in the concept of integrated research and is able to support inter-disciplinary approaches for soil protection and management (Table 1). This could be one of the main assets for the future development of soil micromorphology and its survival in the medium or long term.

Keywords Micromorphology · soil protection strategy · integrated soil research

1 Introduction

A communication from the European Commission to the Council and the European Parliament, entitled: “Towards a thematic strategy for soil protection”, ratified by the 15 ministers of environment of the European Union in 2002 (European Commission 2002), defines five main functions of soil for human societies and the environment:

1. the production of food and other biomass,
2. the capacity for storing, filtering and transformation,
3. the soil as a habitat and a gene pool,
4. the soil as a physical and cultural environment for humankind, and
5. as a source of raw materials.

In addition, it devices 8 main threats to soil: erosion, decline in organic matter, soil contamination (local and diffuse), soil sealing, soil compaction, decline in soil biodiversity, salinisation, and floods and landslides.

W. E. H. Blum
Institute of Soil Research, Department of Forest and Soil Sciences,
University of Natural Resources and Applied Life Sciences (BOKU),
Vienna, Austria, e-mail: herma.exner@boku.ac.at

S. Kapur et al. (eds.), *New Trends in Soil Micromorphology*,

Table 1 Concept for integrated soil research, based on DPSIR

	Main research goals	Research clusters	Sciences involved
1	To understand the main processes in the eco-subsystem soil, underlying soil quality and soil functions, in relation to land uses and soil.	Analysis of processes related to the threats to soil and their interdependency: erosion, loss of organic matter, contamination, sealing, compaction, decline in biodiversity, salinisation, floods and landslides.	Inter-disciplinary research through co-operation of soil micromorphology, of soil physics, soil chemistry, soil mineralogy and soil biology.
2	To know where these processes occur and how they develop with time.	Development and harmonization and standardisation of methods for the analysis of the **State (S)** of the threats to soil and their changes with time = **soil monitoring**.	Multi-disciplinary research through co-operation of soil sciences with -geographical sciences, -geo-statistics, geo-information sciences (e.g. GIS)
3	To know the driving forces and pressures behind these processes, as related to policy and decision making on a local, regional or global basis.	Relating the 8 threats to **Driving forces (D)** and **Pressures (P)** = cross linking with cultural, social and economic drivers, such as policies (agriculture, transport, energy, environment etc.) as well as with technical and ecological drivers, e.g. global and climate change.	Multi-disciplinary research through co-operation of soil sciences with political sciences, legal sciences, social sciences, economic sciences, historical sciences, philosophical sciences and others.
4	To know the impacts on the eco services provided by the sub-system soil to other environmental compartments (eco-subsystems).	Analysis of the **Impacts (I)** of the threats, relating them to soil eco-services for other environmental compartments: air, water (open and ground water), biomass production, human health, biodiversity, culture.	Multi-disciplinary research through co-operation of soil sciences with geological sciences, biological sciences, toxicological sciences, hydrological sciences, physio-geographical sciences, sedimentological sciences and others.
5	To have operational tools (technologies) at one's disposal for the mitigation of threats and impacts.	Development of operational procedures for the mitigation of the threats = **Responses (R)**.	Multi-disciplinary research through co-operation of natural sciences with engineering sciences, technical sciences, physical sciences, mathematical sciences and others.

From 2002–2005, about 400 scientists from all over Europe worked together in an operational set-up of 5 working groups. Their reports are available on the soil internet site (http://europa.eu.int/comm/environment/soil/index.htm) or at the soil electronic library and discussion site CIRCA. In the following, the outcome of the working group on research is of major importance, because it develops new concepts and directions (Blum et al. 2004a,b).

The specific task was to use the DPSIR approach, distinguishing between driving forces (D), which develop pressures (P), resulting in a state (S), which by itself creates impacts (I) and for which responses (R) are needed (European Environment Agency 1999).

This approach allows for key questions to be answered in the understanding of complex soil and environmental systems, such as: (1) what is the D behind a problem?, (2) what are the Ps deriving from the Ds?, (3) what is the S, which the P creates?, (4) what are the Is that result from the S?, and (5) it also allows Rs to change the Ds in order to alleviate or reverse a problem, developing solutions through the implementation of operational measures.

Based on this approach, a new concept for integrated research in soil protection and soil resource management was developed (Table 1). From this table, the 5 main research goals as well as the 5 main research clusters, which are needed to reach these goals, and the sciences which have to be involved, can be identified. Special importance for micromorphology is the first research cluster, targeting at the analysis of soil processes which can only be performed by inter-disciplinary research.

2 The Role of Soil Micromorphology

The primary role of soil micromorphology within this new concept could be to link the different soil disciplines, like soil physics, chemistry, mineralogy, soil biology together by providing a basis on which they can co-operate. This means that soil micromorphology acts as an integrating tool for all soil disciplines involved.

The comparative advantage of micromorphology is its capacity to develop three-dimensional models for describing the complexity of soil, especially regarding the pore system which is the spatial basis for all physical, chemical and biological soil processes. In this context, the walls of the pores, which contain humic substances, clay minerals, oxides and others, and the pore space itself, in which, besides air and water, living organisms such as fungi, bacteria and others are actively participating in soil processes, are of main importance. Soil micromorphology has a central function in the concept of integrated research and is able to support inter-disciplinary approaches for soil protection and management (Table 1). This could be one of the main assets for the future development of soil micromorphology and its survival in the medium or long term.

It can be summarized that the new research concepts, developed within the European Soil Thematic Strategy, underline the importance of soil micromorphology as an integrating soil discipline.

References

Blum WEH, Büsing J, Montanarella L (2004a) Research needs in support of the European thematic strategy for soil protection. Trends in Analytical Chemistry 23: 680–685

Blum WEH, Barcelo D, Büsing J, Ertel T, Imeson A, Vegter J (2004b) Scientific Basis for the Management of European Soil Resources – Research Agenda. Verlag Guthmann-Peterson, Wien

European Commission (2002) Towards a Thematic Strategy for Soil Protection. COM (2002) 179 final (eur-lex.europa.eu/LexUriServ/site/en/com/2002/com2002_0179en01.pdf)

European Environment Agency (1999) Environment in the European Union at the turn of the century. Environmental assessment report No. 2. EEA, Luxembourg (ISBN 92-9157-202-0)

Soil Micromorphology and Soil Hydraulics

Marcello Pagliai and Miroslav Kutilek

Abstract The characterization of soil porosity by micromorphological approach is largely used to evaluate the modification of soil structure induced by the impact of agricultural activity. On the contrary, few studies are addressed to the characterisation of soil porosity to evaluate water movements in soils in spite of the fact that soil hydraulic functions are strongly dependent on the soil porous system. The physical interpretation of one of these functions, the saturated hydraulic conductivity, by soil micromorphological parameters have been studied in a loam soil, representative of the hilly environment of Italy, cultivated to maize.

Besides the confirmation that the continuous conventional tillage induced soil structure degradation in terms of reduction of soil porosity and particularly elongated pores, this paper showed a significant correlation between the elongated continuous transmission pores and the saturated hydraulic conductivity. Results clearly showed that the shape, the size, the orientation and the continuity of pores regulated the flux of the saturated hydraulic conductivity. The micromorphological research also showed that the walls of pores plays an important role on the stability of pores. Formation and existence of the vesicular pores, combined with the orientation of elongated pores parallel to the soil surface is the main factor of the substantial decrease in hydraulic conductivity.

Further research should include all the existing information on pore micromorphology into physically based soil hydraulic functions.

Keywords Soil thin sections · soil porous system · elongated transmission pores · image analysis · saturated hydraulic conductivity

---

Marcello Pagliai
CRA – Centro di ricerca per l'agrobiologia e la pedologia,
Piazza M. D'Azeglio 30 – 50121 Firenze, Italy, e-mail: marcello.pagliai@entecra.it

Miroslav Kutilek
Emeritus Professor, Nad Patankou 34, 160 00 Prague 6, Czech Rep.
e-mail: miroslav.kutilek@volny.cz

S. Kapur et al. (eds.), *New Trends in Soil Micromorphology*,

1 Introduction

The soil water retention curve, the saturated hydraulic conductivity and the unsaturated hydraulic conductivity function are basic soil hydraulic functions and parameters. Ample apprehension of the soil hydraulic functions and parameters is required for a successful formulation of the principles leading to sustainable soil management, agricultural production and environmental protection. From these, all the other parameters, required in the solution of the practical tasks, are derived.

The basic soil hydraulic functions are strongly dependent upon the soil porous system. The development of models is characteristic by the gradual transition from the simplest concepts up to the sophisticated approaches, which should correspond to the visual reality studied by soil micromorphology.

2 Soil Porous System and Soil Micromorphometry

2.1 An Overview on the Quantification of the Soil Porous System

Quantification of the soil porous system consists of classification of soil pores, characterization of the soil pores shapes and the estimation of the pore size distribution function.

When the hydraulic functions of the soil pores are considered, the following laws of hydrostatics and hydrodynamics are applied as best fitting to the classification criteria of the size of the pores (Kutilek and Nielsen 1994, p. 20, Kutilek 2004):

A. Submicroscopic pores that are so small that they preclude clusters of water molecules from forming fluid particles or continuous water flow paths.
B. Micropores, or capillary pores where the shape of the interface between air and water is determined by the configuration of the pores and by the forces on the interface. The resulting air-water interface is the capillary meniscus. The unsaturated flow of water is described by the Darcy-Buckingham equation. The category of micropores is further subdivided into two sub-categories:
    B1. Matrix (intra-aggregate, intrapedal) pores within soil aggregates or within blocks of soil, if aggregates are not present. The shape and size of pores in aggregates as well as coating of the particles, cutans and nodules depend on soil genesis. Aggregates may or may not be stable during the transport of water and thus the porous system may change. Due to the cutaneous film-like forms, which cover the surface of the majority of aggregates, the saturated conductivity at the surface of stable aggregates is usually strongly reduced when compared with that inside the matrix of aggregates (Horn 1994).

- B2. Structural (inter-aggregate, interpedal) pores between the aggregates. Since the shape and size of aggregates depend on soil genesis and soil use, the morphology of pores between aggregates depends upon the soil genesis and soil use. The eventual aggregate instability influences the configuration of structural pores when the soil water content is changed destroying even a certain portion of the structural pores. On the other hand side the porous system has a high stability when the aggregates are formed by the pedo-edaphon. Structural pores are sometimes interpreted as macropores with capillarity, or macropores where Richards equation is applicable. The equivalent pore radius of the boundary separating the two subcategories is in broad ranges from 2 to 50 m, being dependent on the soil taxon and the type of soil use (Kutilek et al., 2006). It is not appropriate to consider a fixed value of the boundary between the two subcategories. Its value is determined either by soil micromorphology (Pagliai and Vignozzi 2003), or from the derivative curve to soil water retention curve, where two or three peaks appear. One peak is characteristic for matrix pores (Sect. 2.1) and one or two peaks for structural pores (Sect. 2.2) (Othmer et al. 1991, Durner 1992).

C. Macropores, or non-capillary pores of such a size, that capillary menisci are not formed across the pore and the shape of air-water interface across the pore is planar. The boundary between micropores and macropores is approximated by the equivalent pore radius 1–1.5 mm. The flow in macropores is described either by a modified Chézy equation or by the kinematic wave equation (Germann and Beven 1985). A more detailed classification of macropores is related to their stability and persistence in time:

  - C1. Macropores formed by the activity of pedo-edaphon such as decayed roots, earthworm channels etc. Their main characteristic is their high stability and persistence in time.
  - C2. Fissures and cracks occurring as a consequence of volumetric changes of swelling-shrinking soils. They have planar form and they close when the soil matrix is saturated with water.
  - C3. Macropores originating due to soil tillage. The depth of their occurrence is limited and they disappear usually in less than one vegetation season. Their persistence depends on the genetic evolution of the soil, meteorological conditions and the type of plants being grown.

The accelerated flux in macropores and structural micropores is usually denoted as preferential flow. With the technique of image analysis it is now possible to characterize soil structure by the quantification of soil pore shape, size, distribution, irregularity, orientation, continuity, etc. in thin sections, prepared from undisturbed soil samples (Bouma et al. 1977, Pagliai et al., 1983, 1984, Pagliai 1988).

The pore size distribution is usually approximated by the lognormal distribution function, but the gamma distribution function was proposed, too (Brutsaert 1966). Pachepsky et al. (1992) and Kosugi (1994, 1999) used the analytical form of the soil hydraulic functions for pore size lognormal distribution and Kutilek (2004) applied this procedure for bi-modal soils distinguishing between the structural and matrix domains of pores.

The pore size distribution is a dynamic property. It is dependent on the water content especially in fine textured soils that are subjected to swelling and shrinkage (Kutilek and Nielsen 1994). Large number of studies exist that show the changes of pore size distribution in Vertisols at different water contents, i.e. when they are water saturated after the rain and the cracks are closed due to saturation and when they are dried and the cracks are open (Schweikle 1982, Kutilek 1983, 1996, Bui et al. 1989). The changes of pore size distribution are strictly correlated with the changes of hydraulic conductivity (Kutilek 1996).

2.2 An Overview on the Soil Micromorphometry

The morphometric technique has the advantage that the measurement and the characterization of pore space can be combined with a visual appreciation of the type and distribution of pores in soil at a particular moment in its dynamic evolution. In soil micromorphological studies the classification of pores according to their size and functional characteristics is restricted to fixed constant boundaries and this is the main difference from the hydraulic approach. Table 1 reports the most frequently used classification scheme of pores proposed by Brewer (1964). Values used by Greenland (1977) are given in Table 2.

The very fine pores less than 0.005 μm, called "bonding spaces", are critically important in terms of the forces holding domains and aggregates of primary particles together; pores of less than 0.5 μm are the "residual pores" for the chemical interactions at the molecular level; pores which have an equivalent pore diameter ranging between 0.5 and 50 μm are the "storage pores", i.e. the pores that store water for plants and for micro-organisms; and the pores ranging from 50 to 500 μm are those called "transmission pores" in which the movement of water is important for plants, and, moreover, they are the pores needed by feeding roots to grow into. The water content, when pores larger than 50 μm have drained, corresponds approximately to the field capacity of the soil. The wilting point commences when most pores larger than approximately 0.5 μm are emptied.

Table 1 Morphologic pore size classification according to Brewer (1964)

Class	Subclass	Class limits (Equivalent diameter μm – 10^{-6} m)
Macropores	Coarse	above 5000
	Medium	2000–5000
	Fine	1000–2000
	Very Fine	75–1000
Mesopores		30–75
Micropores		5–30
Ultramicropores		0.1–5
Cryptopores		less than 0.1

Table 2 Classification of soil pores according to their size. Modified from Greenland (1977)

Equivalent diameter μm (10^{-6} m)	Water potential (bar)	Name
<0.005	>–600	Bonding space
0.005–0.5	–600/–6	Residual pores
0.5–50	–6/–0.06	Storage pores
50–500	–0.06/–0.006	Transmission pores
>500	<–0.006	Fissures

Pores larger than 500 μm can have some useful effects on root penetration and water movement (drainage), especially in fine-textured soils. However, a high percentage of this type of pore (above 70−80% of the total porosity) in soils is usually an index of poor soil structure, especially in relation to plant growth. This is because surface cracks, which develop after the rainfall, when the stability of soil aggregates is poor, belong to this size class (Pagliai et al. 1983). Until now, the necessary proportion of large pores for air and water transmission and easy root growth has generally been inadequately defined. In fact, adequate storage pores (0.5−50 μm) as well as adequate transmission pores (50−500 μm) are necessary for plant growth.

Using the image analysis, the shape factors allow division of pores into different shape groups such as, more or less rounded (regular), irregular, and elongated pores (Bouma et al. 1977, Pagliai et al. 1983). Pores of each shape group can be further subdivided into a selected number of size classes according to either the equivalent pore diameter for rounded and irregular pores or the width for elongated pores.

The regular pores are obviously those of a rounded shape and can be separated in two types according to their origin: the spherical pores formed by entrapped air during soil drying and the channels and chambers formed by biological activity (root growth and movement of soil fauna). Their distinction on soil thin sections is very evident, because spherical pores (vesicles, according to Brewer 1964) have very smooth walls, while channels, even though cut in a transversal mode on thin section, have rough walls with deposits of insect excrements or root exudates. The presence of many spherical pores of the first type (vesicles) creates a vesicular structure typical of soils with the evidence of degradation.

The irregular pores are the common soil voids that have irregular walls (vughs, according to the micromorphological terminology of Brewer 1964) and can be isolated as packing voids or interconnected. The presence of these pores produces the typical vughy structure (Bullock et al. 1985). In cultivated soils these pores can be produced by soil tillage implements as suggested by Kutilek (2004).

Two types of elongated pores can be distinguished, i.e., cracks and thin fissures (planes). The former are typical of clay soils with a depleted soil organic matter content and they are visible at the surface when the soil is dry. The thin fissures are the most important, especially from an agronomic point of view. They are the typical elongated transmission pores (Greenland 1977, Pagliai and Vignozzi 2003) being one part of the structural pores according to Kutilek (2004).

Using the image analysis each pore shape group can be further subdivided into a selected number of size classes according to either the equivalent pore diameter for rounded and irregular pores or the width for elongated pores. The equivalent pore diameters are calculated from the area of the regular and irregular pores, while the width of elongated pores is calculated from their area and perimeter data using a quadratic equation because it is assumed that elongated pores are long narrow rectangles (Pagliai et al. 1984).

The development of micromorphological techniques together with image analysis allows the improvement of hydraulic models. For example, Bouma et al. (1977) developed a method based on the preparation of undisturbed soil columns, saturated and then percolated with a 0.1% solution of methylene-blue that is adsorbed by the soil particles on the pore walls followed by the preparation of vertical and horizontal thin sections. Pores are divided into three shape groups as already explained above and then the pore size distribution is determined. For the planar elongated pores the total area, the area of the blue-stained pore walls, and their lengths, and the spatial distribution of the widths and lengths of the pores with blue-stained walls are determined. Particular attention should be paid to the measurement of the width of the necks of elongated pores because the hydraulic conductivity is determined by the necks in the flow system.

Following the above mentioned procedure the hydraulic conductivity (K_{sat}) can be calculated as proposed by Bouma et al. (1979). Further studies of Bouma (1992) confirmed that morphological information on the soil pore system is essential for the realisation of water flux models. The evolution of software for image analysis, that enables the acquisition of precise information about shape, size, continuity, orientation, and arrangement of pores in soil, permits the simplification of the modelling approach.

3 A Case of Study

3.1 Aim of the Study

The aim of this study was to emphasize the importance of the complete characterization of soil porosity, by micromorphological methods, in order to evaluate the hydraulic conductivity in a loam soil, representative of the hilly environment of Italy, cultivated by maize. Such a correlation is fundamental to improve the actual models of water movements in soils.

4 Materials and Methods

4.1 Soil

The soil is located in the field experiments at the Fagna Agricultural Experimental Centre (Scarperia – Firenze) of the Research Institute for Soil Study and Conservation

Table 3 Main physical and chemical characteristics of the soil

Sand (g kg^{-1})	400
Silt (g kg^{-1})	422
Clay (g kg^{-1})	178
CEC (me/100 g)	14.6
pH (1:2.5) H_2O	8.1
Organic matter (%)	1.4
$CaCO^3$ (%)	5.2
Total N (Kjieldahl) (g kg^{-1})	1.1
C/N	7.4

(Firenze, Italy). It is on a loam soil classified as Typic Haplustept (USDA 1999) or Lamellic Calcaric Cambisol (FAO-IUSS-ISRIC 1998). Some major characteristics of the soil are reported in Table 3.

The field experiment was established in 1994 and three replicates of each of three management practices were tested in 50 m × 10 m plots. The tillage treatments were: (1) minimum tillage (harrowing with a disc harrow to a depth of 10 cm); (2) conventional deep tillage (mouldboard ploughing to a depth of 40 cm) and (3) ripper subsoiling to a depth of 50 cm.

The soil had been cultivated with maize since 1970 adopting the same traditional management practices and, since 1980, the fertilisation has been mineral alone without any addition of farmyard manure or other organic materials.

4.2 Soil Porosity Measurements

The pore system was characterised by image analysis on thin sections from undisturbed soil samples to measure pores $>50\,\mu m$ (macroporosity). Six series of six replicate undisturbed samples were collected in the surface layer (0−100 mm) of each plot at the ripening time of the maize in September 2004. Due to the high variability in conventionally tilled plots an additional series of six replicate undisturbed samples were collected in one of these plots. In total 114 thin sections were prepared and each value reported represents the mean of six thin sections.

Samples were dried by acetone replacement of water (Murphy 1986), impregnated with a polyester resin and made into 60 3 70 mm, vertically oriented thin sections of 30 μm thickness (Murphy 1986). IMAGE PRO-PLUS software produced by Media Cybernetics (Silver Spring, MD, USA) calculated pore structure features from digital images of the thin-sections, using the approach described by Pagliai et al. (1984). The analysed image covered 45 3 55 mm of the thin section, avoiding the edges where disruption can occur. Total porosity and pore distribution were measured according to pore shape and size, the instrument being set to measure pores larger than 50 μm. Pore shape was expressed by a shape factor [$perimeter^2$/ (4π.area)] so that pores could be divided into regular (more or less rounded) (shape factor 122), irregular (shape factor 225) and elongated (shape factor .5). These classes correspond approximately to those used by Bouma et al. (1977). Pores of each shape group were further subdivided into size classes according to either their equivalent pore diameter (regular and irregular pores), or their width (elongated pores) (Pagliai et al. 1983, 1984). Thin sections were also examined using a Zeiss "R POL" microscope at 25 3magnification to observe soil structure, i.e. to gain a qualitative assessment of the structure.

4.3 Saturated Hydraulic Conductivity

To measure saturated hydraulic conductivity, in areas adjacent to those sampled for thin section preparation, the same series of six undisturbed cores for each plot (57 mm diameter and 95 mm high) were collected in the surface layer (0−100 mm). The samples were slowly saturated and the saturated hydraulic conductivity was measured using the falling-head technique (Klute and Dirksen 1986).

5 Results and Discussion

Previous studies (e.g., Pagliai et al. 2004) reported that conventional ploughing induced the more relevant modification of soil physical properties resulting in damage to soil structure. The negative aspects associated with this management system are the formation of surface crusts. The formation of the crusts and the decrease of porosity, in particular the continuous elongated pores, in the surface layers of conventionally tilled soil, besides a reduction of water movement, may also hamper root growth. Minimum tillage and ripper subsoiling could be a good alternative to conventional ploughing.

The combination image analysis-micromorphological observations on thin section prepared from undisturbed soil samples allows the complete characterization of the soil porous system and the quantification of the above mentioned aspects of soil degradation and can also help to understand and to explain differences in water movement.

Figure 1 shows a linear correlation between porosity, represented by pores larger than 50 μm measured on soil thin sections, and saturated hydraulic conductivity,

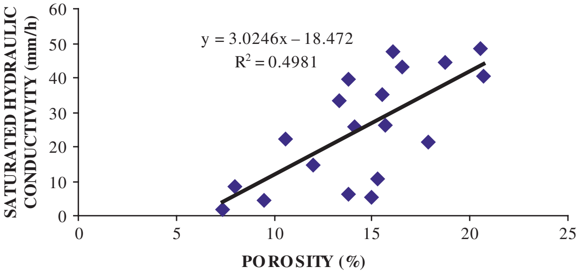


Fig. 1 Correlation between soil porosity, formed by pores larger than 50 μm, and saturated hydraulic conductivity in the surface layer (0–10 cm) of a loam soil (Lamelli-Calcaric Cambisol, according to FAO-IUSS-ISRIC classification, 1998) cropped with maize

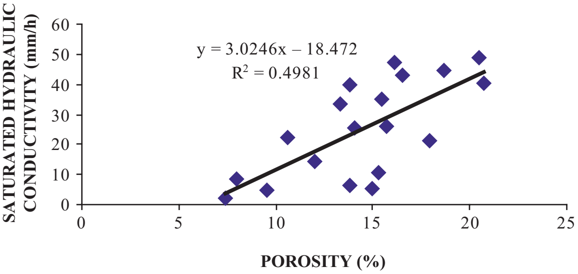


Fig. 2 Correlation between elongated pores larger than 50 µm, and saturated hydraulic conductivity in the surface layer (0–10 cm) of a loam soil (Lamelli-Calcaric Cambisol, according to FAO-IUSS-ISRIC classification, 1998) cropped with maize

measured on undisturbed cores (57 mm × 95 mm) collected in the surface layer (0 − 100 mm), in areas adjacent to those sampled for thin section studies.

As already mentioned, the hydrological flux is regulated by elongated and continuous pores, therefore, such a correlation is strictly connected with the proportion of these pores. The correlation increased only when the elongated pores were taken into consideration, as reported in Fig. 2, while it was completely absent with regular and irregular pores. However, in Fig. 2 it is evident how some values diverged from the linear correlation. The microscopic examination of soil thin sections revealed that in the surface layer of samples collected in conventionally tilled plots a surface crust was present and the elongated pores were parallel oriented to the soil

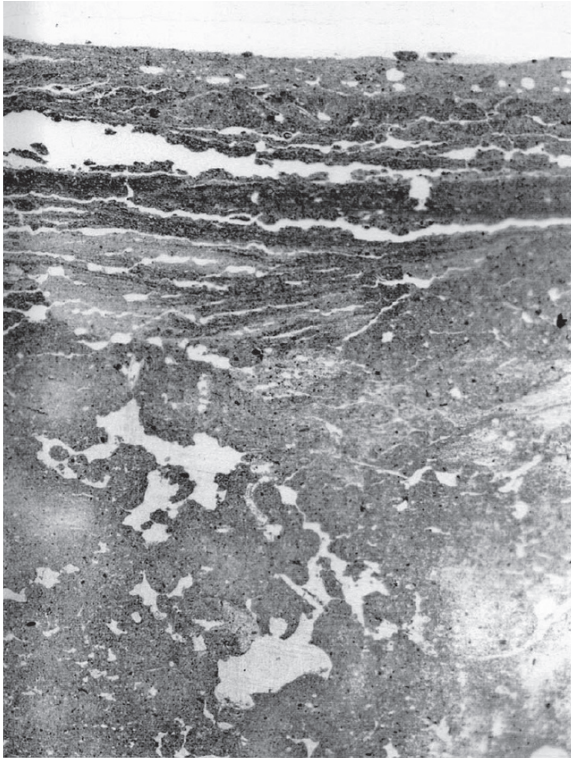


Fig. 3 Microphotograph of a vertically oriented soil thin section prepared from undisturbed samples from the surface layer (0–100 mm) of a loam soil (Lamelli-Calcaric Cambisol, according to FAO-IUSS-ISRIC classification, 1998). Surface crust formation is very evident and the elongated pores are parallel oriented to the soil surface. The white areas represent the pores. Frame length 3 × 5 mm

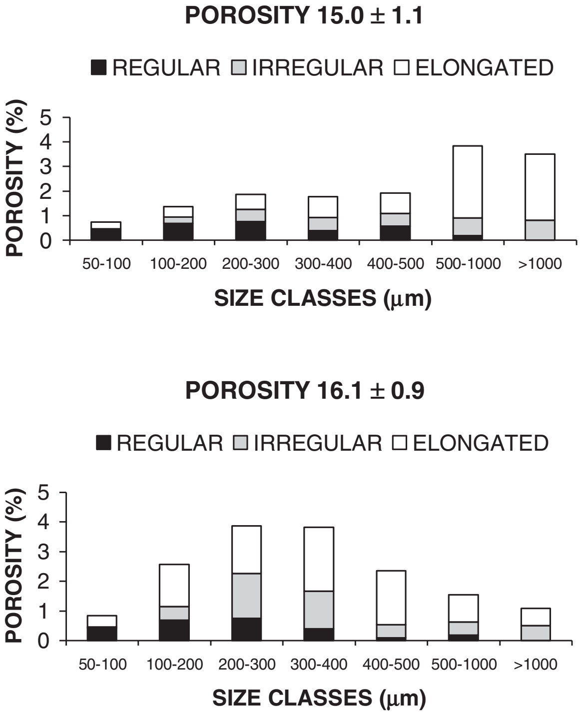
surface without continuity in a vertical sense (Fig. 3), with a disadvantage for water infiltration (Bui and Mermut 1989). Besides the elongated pores parallel to the soil surface, the indicators of soil degradation, i.e., the regular pores-vesicles-formed by entrapped air during the drying processes that do not conduct water, were also observed in the thin sections.

On the contrary, Fig. 4 shows a subangular blocky structure representatives of samples collected in plots under ripper subsoiling. The soil aggregates are separated by elongated continuous pores (planes), are of different sizes and can be rather porous inside. The walls of these elongated pores are moderately regular which do not perfectly accommodate each other. Therefore, these pores permit water movement even when the soil is wet and fully swollen (Pagliai et al. 1984). In contrast, the very regular elongated pores are flat and smooth pores with accommodating faces, which tend to seal when the soil is wet, thus preventing water movement. From an agronomic point of view, the subangular blocky structure is the best type of soil structure because the continuity of elongated pores allows good water movement and facilitates root growth. Moreover, it is a rather stable soil structure.

The visual appreciation of the differences between Figs. 3 and 4 can be quantified as reported in Fig. 5. This Figure represents the pore shape and size distribution of samples taken in the surface layer (0−100 mm) of conventionally tilled plots, in

Fig. 4 Microphotograph of a vertically oriented soil thin section prepared from undisturbed samples from the surface layer (0–100 mm) of a loam soil (Lamelli-Calcaric Cambisol, according to FAO-IUSS-ISRIC classification, 1998) cropped with maize, showing an example of subangular blocky structure, where the aggregates are separated and surrounded by elongated continuous pores. The white areas represent the pores. Frame length 3 × 5 mm

Fig. 5 Correlation between elongated continuous pores larger than 50 μm, and saturated hydraulic conductivity in the surface layer (0–10 cm) of a loam soil (Lamelli-Calcaric Cambisol, according to FAO-IUSS-ISRIC classification, 1998) cropped with maize



which a surface crust was pronounced, as reported in Fig. 3 and in the surface layer of plots under ripper subsoiling, showing a type of soil structure like those represented in Fig. 4. The total macroporosity was statistically similar (around 15% of area occupied by pores larger than 50 μm per thin section), but the pore shape and size distribution were quite different.

Pore shape and size distribution analysis revealed that the proportion of elongated transmission pores (50−500 μm) was lower in conventionally tilled plots than in plots under ripper subsoiling. In the conventionally tilled plots the great part of elongated pores were larger than 500 μm and generally parallel oriented to the soil surface as shown in Fig. 4. Also the irregular pores ("vughs") larger than 500 μm were higher in these plots. Many of these pores are the macropores originated by the tillage with mouldboard plough. The proportion of rounded pores in the range 50−500 μm was higher in conventionally tilled plots and these pores were represented by vesicles formed by entrapped air during soil drying (Fig. 3), so isolated in the soil matrix and, therefore, not conducting water. On the contrary, the regular pores in samples from plots under ripper subsoiling were mainly represented by channels, particularly root channels, conducting water. The higher proportion of elongated transmission pores (50−500 μm), that are important for water movement and for maintaining a good soil structure (Greenland 1977), associate to the presence of channels in soils under ripper subsoiling explained the higher value of saturated hydraulic conductivity, in comparison with conventionally tilled plots.

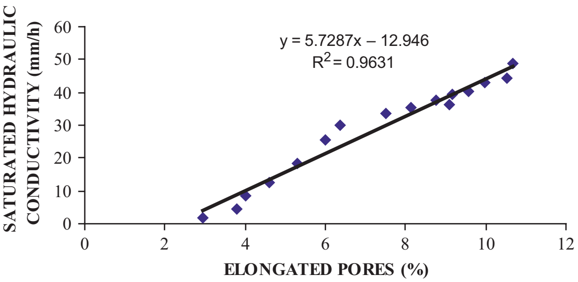


Fig. 6 Correlation between elongated continuous pores larger than 50 µm, and saturated hydraulic conductivity in the surface layer (0–10 cm) of a loam soil cropped with maize

The pore shape and size distribution in the surface layer of the minimum tilled plots showed, approximately, the same trend of that of soils under ripper subsoiling.

When the elongated pores were continuous in a vertical sense, as shown in Fig. 4, the correlation between the elongated pores and hydraulic conductivity was highly significant (Fig. 6).

Combined with image analysis, the use of fractal and fractal fragmentation models can help to characterize the geometry of a porous medium in relation to the transport process (Kutilek and Nielsen 1994). For example, the model of fractal fragmentation leads to a better understanding of the relationships between aggregation, n-modal porosity and soil hydraulic properties.

6 Conclusions

Results of this study indicated that a significant correlation exists between elongated continuous transmission pores and saturated hydraulic conductivity. The shape of the walls of pores plays an important role upon the stability of pores. The formation and existence of the vesicular pores is the main indicator of soil degradation and, combined with the orientation of elongated pores parallel to the soil surface, is the main factor of substantial decrease in hydraulic conductivity.

To preserve a good soil structure, preventing soil degradation, it is important to adopt those management practices that, in the long term, are able to promote a subangular blocky structure with a good proportion of elongated transmission pores, like the ripper subsoiling or minimum tillage.

This study also demonstrated the importance of pore characterisation to understand water movements in soils. Despite the information that can be obtained, the micromorphological research of the soil porous system did not proceed beyond the correlation to saturated conductivity. The next step in the future study on relations between soil micromorphology and hydraulic functions should be focused to the unsaturated conductivity function and mainly to the role of elongated pores upon this function in the structural domain.

Physical models of? soil hydraulic functions (soil water retention function and unsaturated hydraulic conductivity function) fitting to a certain type of morphological structure are still missing. The first step in linking soil hydraulics to soil micromorphology was performed when soil hydraulic functions were based upon the log-normal pore size distribution.

Acknowledgments This research was supported by the Czech Grant Agency, GACR 103/05/2143 and the Special Project "SUOLO" (D.M. 359/7303/01, 30 October 2001) of the Italian Ministry of Agriculture.

References

Bouma J (1992) Influence of soil macroporosity on environmental quality. Advances in Agronomy, 46: 1–37.

Bouma J, Jongerius A, Boersma OH, Jager A, Schoonderbeek D, (1977) The function of different types of macropores during saturated flow through four swelling soil horizons. Soil Sci. Soc. Am. J., 41, 945–950.

Bouma J, Jongerius A, Schoonderbeek D (1979) Calculation of saturated hydraulic conductivity of some pedal clay soils using micromorphometric data. Soil Sci. Soc. Am. J., 43, 261–264.

Brewer R (1964) Fabric and Mineral Analysis of Soils. John Wiley, New York, 470 pp.

Brutsaert W (1966) Probability laws for pore size distribution. Soil Sci., 101, 85–92.

Bui EN, Mermut AR, Santos MCD (1989) Microscopic and Ultra Microscopic Porosity of an Oxisol as Determined by Image Analysis and Water Retention. Soil Sci. Soc. Am. J., 53, 661–665.

Bui EN, Mermut AR (1989) Study of Orientation of Planar Voids in Vertisols and Soils with Vertic Properties Soil Sci. Soc. Am. J., 53, 171–178.

Bullock P, Fedoroff N, Jongerius A, Stoops G, Tursina T (1985) Handbook for soil thin section description. Waine Res. Pub., Wolverhampton.

Durner W (1992) Predicting the unsaturated hydraulic conductivity using multi-porosity water retention curves. In: van Genuchten, M.Th., Leij, F.J. and Lund, L.J. (Eds.), Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils. University of California, Riverside, CA, USA, pp.185–202.

FAO-IUSS-ISRIC (1998) World Reference Base for Soil Survey. FAO report n° 84.

Germann PF, Beven K (1985) Kinematic wave approximation to infiltration into soils with sorbing macropores. Water Resour. Res., 21, 990–996.

Greenland DJ (1977) Soil damage by intensive arable cultivation: temporary or permanent? Philos. Trans. R. Soc. Lond., 281, 193–208.

Horn R (1994) The effect of aggregation of soils on water, gas and heat transport. In: Schulze, E.D. (Ed.), Flux Control in Biological Systems, Academic Press, 10, pp. 335–361.

Klute A, Dirksen C (1986) Hydraulic conductivity and diffusivity: laboratory methods. In: Klute, A. (Ed.), Methods of Soil Analysis, Part 1, Second Edn. Am. Soc. Agron. Publ., Madison, WI, pp. 687–734.

Kosugi K (1994) Three-parameter lognormal distribution model for soil water retention. Water Resour. Res., 30, 891–901.

Kosugi K (1999) General model for unsaturated hydraulic conductivity for soils with lognormal pore-size distribution. Soil Sci. Soc. Am. J., 63, 270–277.

Kutilek M (1983) Soil physical properties of saline and alkali Vertisols. In: Isotope and Radiation Techniques in Soil Physics and Irrigation Studies. IAEA, Vienna, pp. 179–190.

Kutilek M, Nielsen DR (1994) Soil Hydrology. Catena Verlag, Cremlingen Destedt, Germany.

Kutilek M (1996) Water relations and water management in Vertisols. In: Ahmad, N. and Mermut, A. (Eds.), Vertisosls and Technoloégies for their Management. Elsevier, Amsterdam, pp. 201–230.

Kutilek M (2004) Soil hydraulic properties as related to soil structure. Soil Tillage Res., 79, 175–184.

Kutilek M, Jendele L, Panayiotopolos KP (2006) The influence of uniaxial compression upon pore size distribution in bi-modal soils. Soil Tillage Res., 86, 27–37.