

- Emerson, W.W. 1959. The structure of soil crumbs. *J. Soil Sci.* 10:235–244.
- Emerson, W.W. 1964. The slaking of soil crumbs as influenced by clay mineral composition. *Aust. J. Soil Res.* 2:211–217.
- Emerson, W.W. 1967. A classification of soil aggregates based on their coherence in water. *Aust. J. Soil Res.* 5:47–57.
- Emerson, W.W. 1991. Structural decline of soils, assessment and prevention. *Aust. J. Soil Res.* 29:905–921.
- Emerson, W.W. and G.M.F.Grundy. 1954. The effect of rate of wetting on water uptake and cohesion of soil crumbs. *J. Agr. Sci.* 44:249–253.
- Emerson, W.W. and M.G. Dettman. 1960. The effect of pH on the wet strength of the soil crumb. *J. Soil Sci.* 11:149–158.
- Emerson, W.W., R.D. Bond, and A.R. Dexter. 1978. Modification of soil structure. *J. Wiley & Sons, Chichester, U.K.*
- Emerson, W.W. and D.J.Greenland. 1990. Soil aggregates: formation and stability. In M.F. De Boodt, M.H.B.Hayes and A.Herbillion (eds) "Soil Colloid and Their Associations in Aggregates", Series B, Physics Vol. 25, Plenum Press, New York: 485–511.
- Federer, J. 1988. *Fractals*. Plenum Press, New York.
- Fitzpatrick, E.A. 1993. *Soil microscopy and micromorphology*. Wiley, New York.
- Fitzpatrick, E.A., L.A.Mackie, and C.E.Mullins. 1985. The use of plaster of paris in the study of soil structure. *Soil Use and Management* 1:70–72.
- Gabriels, D.M., W.C.Moldenhauer, and D.Kirkham. 1973. Infiltration, hydraulic conductivity and resistance to water drop impact of clod beds as affected by chemical treatment. *Soil Sci. Soc. Am. Proc.* 37:634–637.
- Glass, D.J. 1995. Biotic effects of soil microbial amendments. In: J.E. Rechcigl (ed) "Soil Amendments: Impacts on Biotic Systems," Lewis Publishers, Boca Raton, FL: 251–302.
- Golchin, A., J.M. Oades, J.O.Skjemstad, and P.Clarke. 1994. Soil structure and C cycling. *Aust. J. Soil Res.* 32:1043–1068.
- Golchin, A., J.A.Baldock, and J.M.Oades. 1997. A model linking organic matter decomposition, chemistry and aggregate dynamics. In R.Lal, J.M.Kimble, R. Follett and B.A. Stewart (eds) "Soils and the Carbon Cycle", CRC, Boca Raton, FL (In press).
- Grant, C.D. and A.R.Dexter. 1989. Generation of microcracks in moulded soils by rapid wetting. *Aust. J. Soil Res.* 27:169–182.
- Grant, C.D. and A.V.Blackmore. 1991. Self-mulching behavior in clay soils: Its definition and measurement. *Aust. J. Soil Res.* 29:155–173.
- Greenland, D.J. 1965a. Interaction between clays and organic compounds in soils. Part 1. Mechanisms of interaction between clays and defined organic com-pounds. *Soils and Fertilizers* 28:415–425.
- Greenland, D.J. 1965b. Interaction between clays and organic compounds in soils. Part 2. Adsorption of soil organic compounds and its effects on soil properties. *Soils and Fertilizers* 28:521–532.
- Gupta, R.K. and I.P.Abrol. 1990. Salt-affected soils: their reclamation and manage-ment for crop production. In: R.Lal and B.A.Stewart (eds) "Soil Degradation." *Adv. Soil Sci.* 11:223–287.
- Hakansson, I., W.B.Voorhees, and H.Riley. 1988. Vehicle and wheel factors influencing soil compaction and crop response in different traffic regimes. *Soil & Tillage Res.* 11:239–282.
- Hamblin, A. 1985. The influence of soil structure on water movement, crop root growth, and water uptake. *Adv. Agron.* 38:95–158.
- Hamblin, A. 1991. Sustainable agricultural systems: what are the appropriate measures for soil structure. *Aust. J. Soil Res.* 29:709–715.
- Hargrove, W.L. 1986. Winter legumes as a nitrogen source for no-till grain sorghum. *Agron. J.* 78:70–74.
- Harris, R.F.G., G.Chesters, and O.N.Allen. 1966. Dynamics of soil aggregation. *Adv. Agron.* 18:107–169.

- Hartge, K.H. and R.Horn. 1984. Untersuchungen Zur Gültigkeit des Hookeeschen Gesetzes bei der Setzung von Boden bei Wiederholter Belastung. *Z. AckerPflanzenbau* 153:200–207.
- Hartge, K.H. and B.A.Stewart. 1995. *Soil Structure: Its Development and Function*. Advances in Soil Science, CRC/Lewis Publishers, Boca Raton, FL, 424 pp.
- Haynes, R.J. and M.H.Beare. 1996. Aggregation and organic matter storage in meso-thermal humid soils. In: M.R.Carter and B.A.Stewart (eds) “Structure and Organic Matter Storage in Agricultural Soils.” CRC/Lewis Publishers, Boca Raton, FL.
- Hénin, S. 1938. Etude physico-chimique de la stabilite structurale des terres. Monograph National Center of Agronomic Research. Paris, France: 52–54.
- Hénin, S., G.Monnier, and A.Combeau. 1958. Methode pour l’etude de la stabilite structural des sols. *Ann. Agron.* 9:73–92.
- Horn, R. 1990. Aggregates characterization as compared to soil bulk properties. *Soil & Tillage Res.* 17:265–289.
- Horn, R. and A.R.Dexter. 1989. Dynamics of soil aggregation in a homogenized desert loess. *Soil & Till. Res.* 13:254–266.
- Horn, R., T.Baumgartl, R.Kayser, and S.Baasch. 1995. Effect of aggregate strength and stress distribution in structured soils. In: K.H. Hartge and B.A. Stewart (eds) “Soil Structure: Its Development and Functions.” CRC/Lewis Publishers, Boca Raton, FL: 31–52.
- Jacks, G.V. 1963. The biological nature of soil productivity. *Soils & Fert.* 26: 147–150.
- Janse, A.R.P. and F.F.R.Koenigs. 1963. Structural changes of soils on wetting. *Boor en Spade* 13:168–177.
- Kay, B.D. 1990. Rates of change of soil structure under different cropping systems. *Adv. Soil Sci.* 12:1–52.
- Kay, B.D. 1997. Soil structure and organic carbon: a review. In R. Lal, J.M. Kimble, R. Follett and B.A. Stewart (eds) “Soils and the Carbon Cycle”, CRC, Boca Raton, FL (In press).
- Kay, B.D., C.D.Grant, and P.H.Groenevelt. 1985. Significance of ground freezing on soil bulk density under zero tillage. *Soil Sci. Soc. Am. J.* 49:973–978.
- Kay, B.D., D.A.Angers, P.H.Groenevelt, and J.A.Baldock. 1988. Quantifying the influence of cropping history on soil structure. *Can. J. Soil Sci.* 68: 359–368.
- Kay, B.D. and E.Perfect. 1988. State of the art: heat and mass transfer in freezing soils. *Proc. Int’l Symp. on Ground Freezing*, Nottingham, U.K. Vol. 1:3–22.
- Kay, B.D., D.A.Angers, P.H.Groenevelt, and J.A.Baldock. 1988. Quantifying the influence of cropping history on soil structure. *Can. J. Soil Sci.* 68: 359–368.
- Kember, W.D. and R.C.Rosenau. 1986. Aggregate stability and size distribution. In A. Klute (ed) “Methods of Soil Analysis”, Part 1, American Society of Agronomy Monograph 9, Madison, WI: 425–441.
- Kubiena, W.L. 1938. *Micropedology*. Collegiate Press, Ames, Iowa.
- Lal, R. 1991. Soil structure and sustainability. *J. Sustainable Agric.* 1:67–92.
- Lal, R. 1991. Soil conservation and biodiversity. In D.L. Hawksworth (ed) “The Biodiversity of Microorganisms and Invertebrates: Its Role in Sustainable Agriculture”, CAB International, Wallingford, U.K.: 89–104.
- Lal, R. 1994. Sustainable land use systems and soil resilience. In D.J. Greenland and R. Lal (eds) “Soil Resilience and Sustainable Land Use”, CAB International, Wallingford, U.K.: 41–67.
- Lal, R. 1995. Global soil erosion by water and carbon dynamics. In: R. Lal, J.M. Kimble, E.Levine and B.A.Stewart (eds) “Soils and Global Change.” CRC/Lewis Publishers, Boca, Raton, FL: 131–141.
- Lal, R. 1999. Soil management and restoration for carbon sequestration to mitigate the accelerated greenhouse effect. *Prog. Env. Sci.* 1:307–326.
- Lal, R. 2000. World cropland soils as source or sink for atmospheric carbon. *Adv. Agron.* 71:145–191.
- Lal, R. 2003. Soil erosion and the global carbon budget. *Env. Intl.*: 1–14.

- Lal, R., G.F.Wilson and B.W.Okigbo. 1979. Changes in properties of an Alfisol by various cover crops. *Soil Sci.* 127:377–382.
- Lal, R., D.de Vleeschauwer, and R.M.Nganje. 1980. Changes in properties of a newly cleared Alfisol as affected by mulching. *Soil Sci. Soc. Am. J.* 66: 827–832.
- Lal, R. and O.O.Akinremi. 1983. Physical properties of earthworm casts and surface soil as influenced by management. *Soil Sci.* 135:116–122.
- Lal, R. and N.R.Fausey. 1993. Drainage and tillage effects on a Crosby-Kokomo soil association in Ohio. IV. Soil Physical Properties. *Soil Tech.* 6:123–135.
- Lal, R., A.A.Mahboubi, and N.R.Fausey. 1994. Long-term tillage and rotation effects on properties of a central Ohio soil. *Soil Sci. Soc. Am. J.* 58:517–522.
- Lal, R., P.Henderlong, and M.Flowers. 1997. Forages and row cropping effects on soil organic carbon and nitrogen contents. In R.Lal, J.Kimble, R.Follett and B.A. Stewart (eds) "Management of C Sequestration In Soil", CRC, Boca Raton, FL (In press).
- Lambe, T.W. 1960. The structure of compacted clays. *Trans. Am. Soc. Civil Engrs.* Reprint Paper 3041, 125 pp.
- Larionov, A.K. 1982. *Methods of Studying Soil Structure.* USDA/NSF, Amerind Publishing Co., New Delhi, 193 pp.
- Lavelle, P. and B.Pashanasi. 1989. Soil macrofauna and land management in Peruvian Amazonia. *Pedobiologia* 33:283–291.
- Lee, K.E. 1985. *Earthworms: Their ecology and relationships with soils and land use.* Academia Press, Sydney, Australia.
- Lee, K.E. and R.C.Foster. 1991. Soil fauna and soil structure. *Aust. J. Soil Res.* 29:745–775.
- Letey, J. 1985. Relationship between soil physical properties and crop production. *Adv. Soil Sci.* 1:277–294.
- Levy, G.L. 1996. Soil stabilizers. In: M. Agassi (ed) "Soil Erosion, Conservation and Rehabilitation." M.Dekker, New York: 267–299.
- Logsdale, D.E. and L.R.Webber. 1959. Effect of frost action on structure of Haldimand clay. *Can. J. Soil Sci.* 39:103–106.
- Low, A.J. 1972. Improvements in structural state of soils under leys. *J. Soil Sci.* 6:179–199.
- Lynch, J.M. and E.Bragg. 1985. Microorganisms and soil aggregate stability. *Adv. Soil Sci.* 2:133–171.
- McCalla, T.M. 1944. Water drop method of determining stability of soil structure. *Soil Sci.* 58:117–121.
- Michaels, A.S. 1959. Physico-chemical properties of soils: soil water systems. *Proc. Am. Soc. Civil Engrs. J. Soil Mech. Found. Div.* 85:91–102.
- Middleton, H.E. 1930. Properties of soils which influence soil erosion. *USDA Tech. Bull.* 178, Washington, D.C., 16 pp.
- Mitchell, J.K. 1956. The fabric of natural clays and its relation to engineering properties. *Proc. Highway Res. Board* 35:693–713.
- Molope, M.B., E.R.Page, and I.C.Grieve. 1985. A comparison of soil aggregate stability tests using soils with contrasting cultivation histories. *Comm. Soil Sci. Plant Anal.* 16:315–322.
- Mortland, M.M. 1970. Clay-organic complexes and interactions. *Adv. Agron.* 22: 75–117.
- Murray, R.S. and J.P.Quirk. 1990. Interparticle forces in relation to the stability of soil aggregates. In M.F.De Boodt, M.H.B.Hayes and A.Herbillion (eds) "Soil Colloid and Their Associations in Aggregates", Series B, Physics Vol. 25, Plenum Press, New York: 439–461.
- Oades, J.M. 1990. Associations of colloids in soil aggregates. In M.F.De Boodt, M.H.B. Hayes and A. Herbillion (eds) "Soil Colloid and Their Associations in Aggregates", Series B, Physics Vol. 25, Plenum Press, New York: 463–483.
- Oades, J.M. and A.G.Waters. 1991. Aggregate hierarchy in soils. *Aust. J. Soil Res.* 29:815–828.
- Panabokke, C.R. and J.P.Quirk. 1957. Effects of initial water content on stability of soil aggregates in water. *Soil Sci.* 83:185–195.
- Passioura, J.B. 1991. Soil structure and plant growth. *Aust. J. Soil Res.* 29:717–727.

- Pawluk, S. 1988. Freeze-thaw effect on granular structure reorganization for soil materials of varying texture and moisture content. *Can. J. Soil Sci.* 68:485–494.
- Perfect, E. and B.D.Kay. 1994. Statistical characterization of dry aggregate strength using rupture energy. *Soil Sci. Soc. Am. J.* 58:1804–1809.
- Perfect, E. and B.D.Kay. 1995. Application of fractals in soil and tillage research: a review. *Soil & Till Res.* 36:1–20.
- Peterson, J.B. 1947. Calcium linkage, a mechanism in soil granulation. *Soil Sci. Soc. Am. Proc.* 12:29–34.
- Pieri, C. 1991. *Fertility of soils: A future for farming in the West African savannah.* Springer-Verlag, Berlin.
- Pojasok, T. and B.D.Kay. 1990. Assessment of a combination of wet sieving and turbidimetry to characterize the structural stability of moist aggregates. *Can. J. Soil Sci.* 70:30–42.
- Quirk, J.P. and C.R.Panabokke. 1962. Incipient failure of soil aggregates. *J. Soil Sci.* 13:60–70.
- Revut, I.B. and A.A.Rode. 1981. *Experimental Methods of Studying Soil Structure.* USDA/NSF, Amerind Publishing Co., New Delhi, 530 pp.
- Ringrosa-Voase, A.J. 1991. Micromorphology of soil structure: description, quantification, application. *Aust. J. Soil Res.* 29:777–813.
- Robert, M. and C.Chenu. 1992. Interactions between soil minerals and microorganisms. *Soil Biochem.* 7:307–404.
- Robinson, D.O. and J.B.Page. 1950. Soil aggregate stability. *Soil Sci. Soc. Am. Proc.* 15:25–29.
- Rosenquist, I. Th. 1959. Physico-chemical properties of soils: soil water systems. *Proc. Am. Soc. Civil Engs., J. Soil Mech. Found. Div.* 85:31–53.
- Russell, E.W. 1934. The interaction of clay with water and organic liquid as measured by specific volume changes and its relation to the phenomenon of crumb formation in soils. *Phil. Trans. Roy. Soc. Ser. A* 233:361–390.
- Russell, E.W. 1971. Soil structure: its maintenance and improvement. *J. Sol Sci.* 22:137–151.
- Schloessing, T. 1874. *Ann. Chim. Phys.* [2] 15:514–546.
- Schrader, S., M.Joschko, H.Kula, and O.Larink. 1995. Earthworm effects on soil fabric with emphasis on soil stability and soil water movement. In: K.H. Hartge and B.A. Stewart (eds) "Soil Structure: Its Development and Functions." CRC/ Lewis Publishers, Boca Raton, FL: 109–133.
- Singh, P., R.S.Kanwar, and M.L.Thompson. 1991. Measurement and characterization of macropores by using AUTO-CAD and automatic image analysis. *J. Env. Quality* 20:289–294.
- Skidmore, E.L. and D.H.Powers. 1982. Dry soil-aggregate stability: energy-based index. *Soil Sci. Soc. Am. J.* 46:1274–1279.
- Slater, C.S. and H.Hopp. 1949. The action of frost on the water stability of soils. *J. Agr. Res.* 78:341–346.
- Soil Science Society of America. 1975. *Soil Conditioners*, SSSA, Madison, WI.
- Soil Survey Division Staff. 1951. *Soil Survey Manual*, USD A Handbook No. 18, Washington, D.C.
- Soil Survey Division Staff. 1993. *Soil Survey Manual*. USDA-NRCS Handbook No. 18, Washington, D.C., 437 pp.
- Spoor, G. 1988. Improving the effectiveness of tillage operations. In *Proc. Soil Management 88*. Darling Downs Ins. Adv. Educ., Toowoomba, Qld. Australia.
- Stengel, P. 1990. Characterization of soil structure: objectives and methods. In J. Boiffin and A. Martin la Fliche (eds) "Soil Structure and its Evolution: Agricultural Consequences and its Management". Coll. INRA, France: 15–36.
- Thomasson, A.J. 1978. Towards an objective classification of soil structure. *J. Soil Sci.* 29:38–46.
- Tisdall, J.M. 1991. Fungal hyphae and structural stability of soil. *Aust. J. Soil Res.* 29:729–743.
- Tisdall, J.M. 1996. Formation of soil aggregates and accumulation of soil organic matter. In M.R.Carter and B.A.Stewart (eds) "Structure and Organic Matter Storage in Agricultural Soils", *Advances in Soil Science*, CRC/Lewis Publishers, Boca Raton, FL: 57–96.

- Tisdall, J.M. and J.M. Oades. 1982. Organic matter and water-stable aggregates in soil. *J. Soil Sci.* 33:141–163.
- Tiulin, A.F. 1928. Questions on soil structure. II. Aggregate analysis as a method for determining soil structure. *Perm. Agr. Exp. Sta. Div. Agr. Chem. Rep.* 2:77–112.
- Tiulin, A.F. 1933. Considerations on the genesis of soil structure and on methods of its determination. *Trans. 1st Com. Int. Soc. Soil Sci., Moscow, Vol. A:* 111–132.
- Trollope, D.H. and C.K.Chan. 1959. Soil structure and the Step-strain Phenomena. *J. Soil Mech. Found* 86:1–39.
- Van Bavel, C.H.M. 1949. Mean weight diameter of soil aggregates as a statistical index of aggregation. *Soil Sci. Soc. Am. Proc.* 14:20–23.
- White, E.M. 1966. Subsoil structure genesis: theoretical consideration. *Soil Sci.* 101:135–141.
- White, E.M. 1967. Soil age and texture in sub-soil structure genesis. *Soil Sci.* 103:288–298.
- White, W.M. 1993. Dry aggregate distribution. In M.R.Carter (ed) “Soil Sampling and Methods of Analysis.” Lewis Publishers, Boca Raton, FL: 659–662.
- Williams, W.R. 1935. Thesis of tenacity and cohesion in soil structure. *Pedology* 30:755–762.
- Williams, B.G., D.J.Greenland, and J.P.Quirk. 1967. The effect of poly (vinyl alcohol) on the nitrogen surface area and pore structure of soils. *Aust. J. Soil Res.* 5:77–83.
- Wilson, G.F., R.Lal, and B.N.Okigbo. 1982. Effects of cover crops on soil structure and on yield of subsequent arable crops under strip tillage on eroded Alfisols. *Soil & Tillage Res.* 2:233–250.
- Wilson, D.O. and W.L.Hargrove. 1986. Release of nitrogen from crimson clover residue under two tillage systems. *Soil Sci. Soc. Am. J.* 50:1251–1254.
- Yoder, R.E. 1936. A direct method of aggregate analyses and a study of the physical nature of erosion losses. *J. Am. Soc. Agron.* 28:337–351.
- Yong, R.M. and B.P.Warkentin. 1966. *Introduction to Soil Behavior.* The Macmillan Co., New York, 451 pp.
- Yong, R.M. and B.P.Warkentin. 1975. *Soil properties and behavior.* Elsevier, Amsterdam.
- Youker, R.E. and J.L.McGuinness. 1956. A short method of obtaining mean weight diameter values of aggregate analysis of soils. *Soil Sci.* 83:291–294.
- Zakhrov, S.A. 1927. Achievements of Russian science in morphology of soils. *Russ. Pedolog. Investigations. LL Acad. Sci., USSR.*
- Zakhrov, S.A. 1931. *Kurs Pochvovedeniya (course in soil science).* Izd. ANSSSR, Moscow.

5

Porosity

5.1 GENERAL DESCRIPTION

An aggregate is analogous to a building. The functional space of a building includes rooms, interconnecting corridors, and exit and entrance doors that facilitate communication with the exterior. Stability of the exterior and interior walls is important to maintaining functions of all rooms and interconnecting corridors. Continuity of corridors is extremely important for the building to remain functional. Similar to the walls of a building, skeleton structure of microaggregates and aggregates is important to maintaining size, stability, and continuity of pores within and between aggregates. The porosity, or soil architecture, is the functional entity of soil structure. Soil, similar to a building, becomes dysfunctional as soon as it loses its pores and their continuity within the soil profile and to the atmosphere. Therefore, soil structural characterization cannot be complete without assessment of its porosity, pore size distribution, and continuity. Because aggregates are highly dynamic and transient, varying in time and space and ranging in scale from A to a few cm, so are pores. Porosity is a complex and a moving target, that governs the essence of biological processes that supports life and biochemical and physical processes that determine environment quality. It is this complexity which leads to a wide range of terminology, e.g., porosity, pore, pore space, pore size distribution, voids, channels, biochannels and biopore or macropores, cracks, fissures, fractures, and so on. Therefore, understanding this complexity is important to understanding soil structure.

5.2 TERMINOLOGY

Porosity is a general term used to designate all voids in the soil. There are several systems to designate porosity on the basis of their origin or location within the soil body.

5.2.1 Textural and Structural Porosity

Textural porosity refers to the pores and their size distribution in relation to the particle size distribution. Importance of pores rather than of the size of particles was recognized by Green and Ampt (1911) by stating that “the relations of the soil to the movements of

air and water through it...are much less obscure if we direct our attention to the number and dimensions of the spaces between the particles rather than to the sizes of the particles themselves." Soils of coarse texture and single-grain structure have textural pores in between the large particles. Textural pores are also the intraaggregates pores (see Fig. 4.1). Therefore, the porosity defined by the spatial distribution of soil separates or primary particles is referred to as the "textural porosity."

Primary particles are bonded together to form secondary particles or aggregates, so that in well-aggregated soils the binding between primary particles within an aggregate is stronger than the binding between aggregates. Although these aggregates are transient and vary drastically in temporal and spatial scales, they maintain their integrity at any point in time. Integrity is defined by aggregate size, stability, position, and orientation with respect to one another. Just as primary particles define textural porosity, aggregates define structural porosity (Childs, 1968; Derdour et al., 1993) or inter-aggregate porosity (refer to Fig. 4.1). Structural porosity, total pore volume, and its size distribution and continuity, are extremely important in well-structured soils. Similar to aggregates, structural porosity is a dynamic entity. In addition to endogenous factors that govern aggregation and aggregate size distribution, exogenous factors that affect structural porosity include climate through its effect on wet-dry and freeze-thaw cycles, cropping systems through their effects on root system and other biotic factors, and soil management through tillage and crop residues disposal. In some soils, there are distinct groups of textural and structural pores. In other soils, such a distinction is difficult to make.

5.2.2 Matrix and Non-Matrix Pores

In soil survey terminology, pores are distinguished into three classes: matrix pores, non-matrix pores, and interstructural pores. Matrix pores are formed by the packing of primary soil particles. These are also the textural pores, which are generally small in size. The total volume of matrix pores may change with the soil wetness. Non-matrix pores are large voids created by roots, burrowing animals, action of compressed air, and other agents. The volume of non-matrix pores does not change drastically with change in soil wetness, and is not affected by soil texture. Interstructural pores are defined or delimited by structural units. These are crevices between structural units, and are generally planar.

5.3 METHODS OF EXPRESSION OF SOIL POROSITY

Soil porosity is expressed in numerous ways including total porosity (f_t), aeration porosity (f_a), air ratio (α) and, void ratio (e) (see Chapter 2). Porosity may be expressed in terms of number, size, shape, and vertical/ horizontal continuity of pores.

5.3.1 Number

This visual description is particularly useful for describing the non-matrix pores formed by roots, animals, etc. The number of such pores is expressed per unit area that may be 1 cm^2 for very fine and fine pores, 1 dm^2 for medium and coarse pores, and 1 m^2 for very

coarse pores. The classification used by the Soil Survey Division Staff (1990) to describe non-matrix pores is as follows:

Few: < 1 per unit area
 Common: 1-5 per unit area
 Many: ≥5 per unit area

5.3.2 Pore Size Distribution

Rather than the total pore volume, it is its size and distribution that are important to retention and conduction of fluids in and through the soil. Pores in soils range widely from 0.003 μm plate separation in clay particles to biopores, cracks, and tunnels tens of centimeters in diameter (Hamblin, 1985). In addition to structural pores of pedological origin, a wide range of pores exists of biological origin (Table 5.1). These pores are extremely important in transmission of water and gaseous exchange.

TABLE 5.1 Pore Dimensions of Biological Origin or Significance

Average pore size (μm)	Biological significance
1500–50,000	Ant nests and channels
500–11,000	Wormholes
300–10,000	Tap roots of dicotyledons
500–10,000	Nodal roots of cereals
100–1,000	Seminal roots of cereals
50–100	Lateral roots of cereals
20–50	1st- and 2nd-order laterals
5–10	Root hairs
1,000	Root plus root hair cylinder in clover
30	“Field capacity” (–10 k Pa)
0.5–2	Fungal hyphae
0.2–2	Bacteria
0.1	Permanent wilting point (–1500 k Pa)

1 kPa=10 cm of water column at STP
Source: Adapted from Hamblin, 1985.

Non-matrix or macropores are described in terms of the specified diameter size. Five size classes commonly used in soil survey are:

1. Very fine: <0.5 mm
2. Fine: 0.5–2 mm

3. Medium: 2–5 mm
 4. Coarse: 5–10 mm
 5. Very coarse: >10 mm

Complementary to the visual classification used in soil surveys, numerous other systems have been devised for describing pores of different sizes. These systems may be conveniently grouped into two categories based on size (Table 5.2) and pore functions (Table 5.3). There is evidently a wide discrepancy in the nomenclature, and there exists a strong need for standardization of the terminology. Toward an attempt to standardize, it is suggested that Kay's (1990) classification for size and Greenland's (1977) classification for function be used in pore characterization. In terms of their size, pores of equivalent cylindrical diameter (ECD) $>30\ \mu\text{m}$ are defined as macropores, between 0.2 and $30\ \mu\text{m}$ as mesopores, and $<0.2\ \mu\text{m}$ as micropores. In terms of their functions in relation to plant growth, pores of ECD $>50\ \mu\text{m}$ are described as transmission pores, those between 0.5 and $50\ \mu\text{m}$ as storage pores, and those $<0.5\ \mu\text{m}$ as residual pores. Functions of these pores in relation to plant growth are listed in Table 5.4. Pores $>500\ \mu\text{m}$, especially the biopores, are called fissures, and those $<0.005\ \mu\text{m}$

TABLE 5.2 Some Classification Systems of Soil Pores Based on Their Size Distribution

Reference	Equivalent cylindrical diameter (ECD, μm)	Pore category
Manegold (1957)	100–5000	Voids
	30–100	Capillaries
	0.002–30	Force spaces
Jongerius (1957)	100–5000	Macropores
	30–100	Mesopores
	0.002–30	Micropores
Johnson, et al. (1960)	>5000	Coarse
	2000–5000	Medium
	1000–2000	Fine
	75–1000	Very fine
	<75	Micropores
Brewer (1964)	>5000	Coarse macropores
	2000–5000	Medium macropores
	1000–2000	Fine macropores
	75–1000	Very fine macropores
	30–75	Mesopores
	5–30	Micropores
	0.1–5	Ultramicropores
	<0.1	Cryptopores
IUPAC ^a (1972)	0.1–5000	Macropores
	0.005–0.1	Mesopores
	< 0.005	Micropores
McIntyre (1974)	500–5000	Superpores

	50–500	Macropores
	0.1–50	Minipores
	<0.1	Micropores
Smart (1975)	100–5000	Minipores
	30–100	Macropores
	<30	Micropores
Kay (1997)	>30	Macropores
	0.2–30	Mesopores
	<0.2	Micropores
Soil Survey Division (1990)	>10 mm	Very coarse
	5–10 mm	Coarse
	2–5 mm	Medium
	1–2 mm	Fine
	<0.5 mm	Very fine

^aInternational Union of Pure and Applied Chemistry.

TABLE 5.3 Some Classification Systems of Soil Pores Based on Functional Characteristics

Reference	Equivalent cylindrical diameter (μm)	Classification
Greenland (1977)	< 0.005	Bonding pores
	<0.5	Residual pore
	0.5–50	Storage pore
	50–500	Transmission pore
	>500	Fissures
Luxmoore (1981)	<10	Pressure gradient pore
	10–1000	Gravitational pore
	>1000	Channel-flow pore

TABLE 5.4 Pore Classification in Relation to Pore Function

Name	Equivalent cylindrical diameter (μm)	Function
Transmission pores	>50	Air movement and drainage of excess water.
Storage pores	0.5–50	Retention of water against gravity and release.
Residual pores	0.5–0.005	Retention and diffusion ions in solutions.
Bonding pores	<0.005	Support major forces between soil particles.

are called *bonding pores*. These are the pores that separate clay particles to form quasi crystals or domains (refer to Chapter 4). Readers are referred to a review by Kay (1990; 1998) for conceptual interrelationship among size distribution of aggregates and pores.

5.3.3 Shape and Continuity

Pore shape and geometry are assessed to describe non-matrix pores, most of which are either vesicular (e.g., spherical or elliptical) or tubular (e.g., cylindrical or elongated). Some pores may also be irregular, as is the case in gravelly soils. Continuity and tortuosity of pores are also important to fluid transmission and transport processes in soil, and root growth. Vertical continuity through the horizon is relevant to transport of water across it and gaseous exchange with the atmosphere. The vertical continuity is expressed by assessing the average distance through which the mean pore diameter exceeds 0.5 mm (>fine pores) when soil is moist. Three classes of pores are recognized: low, <1 cm; moderate, 1 to 10 cm; and high, >10cm (Soil Survey Division Staff, 1990).

5.4 ORIGIN AND FORMATION OF PORES

A classification system may also be based on the origin or genesis of soil pores. Macropores or transmission pores are formed by biotic activity, development of shrinkage cracks, formation of ice lenses, activity of soil animals, and tillage operations. Soil organic matter content and clay minerals also play an important role in formation and stabilization of macropores. Further, macropores are strongly influenced by anthropogenic activities, and thus altered by land use and soil management. Mesopores or retention pores are important to plant growth. Mesopores are created by creation of microcracks through shrinkage, freeze-thaw cycles, collapse or plugging of macropores by sedimentation or precipitation, and development of root hair, fungal hyphae, and mycorrhizae. These pores comprise textural porosity and are influenced by particle size distribution, organic matter content, and clay mineralogy, and are only slightly influenced by management. Micropores are created by shrinkage of the soil matrix and collapse of mesopores. Micropores or residual pores are least impacted by soil management and are biologically inactive. These pores are essentially always filled with water, inaccessible to microorganisms, and can be strategically helpful in soil carbon sequestration.

5.5 ASSESSMENT OF POROSITY AND PORE SIZE DISTRIBUTION

There are numerous methods of characterizing porosity, some of which are briefly described in this section.

5.5.1 Total Porosity and Void Ratio

Total porosity (f_t) is usually determined from the bulk density and particle density relationship ($f_t = 1 - \rho_b / \rho_s$). The f_t can also be determined from the saturation moisture content (Θ_s), provided that there is no entrapped air. These relationships hold for non-swelling soils. Void ratio (e) is another indirect measure of porosity, and can also be determined from the bulk density and particle density analysis ($e = \rho_s / \rho_b - 1$) (refer to Chapter 2). In swelling soils, however, in which both the pore volume and bulk volume

change substantially with change in w or Θ , it is more appropriate to compute e than f_t . The e value may range from 0.25 to 0.8 for subsoils and 0.8 to 1.4 for surface soil.

5.5.2 Air-Filled Porosity (f_a)

The air-filled porosity is a measure of the macropores, and is generally measured at field capacity or 60 cm water suction ($f_a = f_t - \Theta_{60\text{cm}}$). Some of these concepts will be explained in Chapter 10 dealing with soil moisture retention. The critical limit of f_a in relation to plant growth is 0.1 for sensitive upland plants (apparently not for the hydromorphic plants such as rice).

5.5.3 Pore Size Distribution

Assessment of the pore size distribution is a principal goal of characterization of soil structure. Similar to the nomenclature, there are also numerous methods of determining the pore size distribution.

Field Methods

Visual Methods. Macropores, comprising cracks and fissures and biochannels, are often determined in the field using visual methods. Fissures and channels are easily visible and can be counted and measured as such (Douglas, 1986). Small pores can be impregnated with a substance that enhances their visibility. A commonly used procedure involves using a super saturated solution of gypsum (CaSO_4), which is poured over the soil. The soil is then removed layer by layer horizontally to assess pore continuity as indicated by transport of gypsum by the pores (Ehlers, 1975). Pores can also be lined with a fluorescent dye (e.g., rhodamine-B dye) to improve their visibility. In a field setting the dye solution (3 g of 45 mm brilliant blue FCF dye dissolved in one liter of deionized water) is uniformly applied on a soil surface (1×1.5 m) for 6 hours using a field sprinkler (Flury and Fluehler, 1995a; b). One day after dye application, a trench of 12 m depth is opened at a distance of 0.3 m from the border of sprinkled area to prepare a vertical profile of 1×1 m. The dye coverage is estimated from the photograph of the stained area. The blue stained areas represent macropores or preferential flow paths (Fig. 5.1). The continuous stained pores can be traced on an acetate sheet. The dye method is usually visible in soils of neutral color. Pictures of impregnated or dye-lined pores can be taken, magnified and pore dimensions assessed in the laboratory using micrometer, planimeters, image analyzer, and other devices (Anderson et al., 1990; Grevers and deJong, 1990). An alternative to staining is the direct measurement

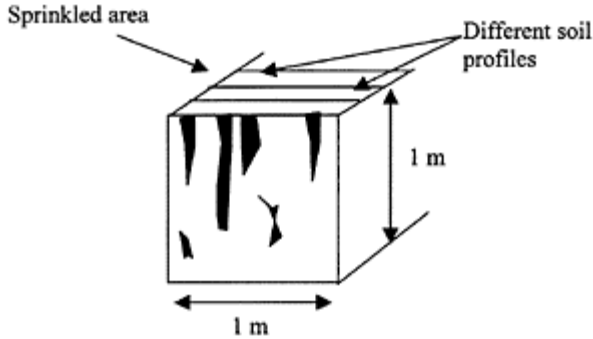


FIGURE 5.1 Schematic of an experimental setup to assess macropores using Brilliant Blue dye-tracer.

technique by x-ray computed tomography (Anderson et al., 1990; Carter and Ball, 1993).

Fractal Analyses. Field assessment of pore size distribution can be described using fractals in three different ways. In the first method, the number-size distribution of voids is obtained in two-dimension by image analysis and is fitted to equation (refer to Chapter 4). These results are then extrapolated to three-dimensions using the relation $D_{R3}=D_{R2}+1$. The parameter b in Eq. (4.19) is related to the air-entry value and provides the measure of length of the largest pore. The parameter k is linked to representative elementary volume, using the equation $a=k^{-DR3}$, where a is the minimum sample length to represent pore size distribution by using soil water retention curve discussed in detail in Chapter 11. In this method, D_{R3} is related to the pore size distribution index (λ) as $D_{R3}=3-1/\lambda$. The third method uses the modified Campbell's function (Ross et al., 1991) to predict zero-relative saturation at a finite tension. The fractal pore space between tensions at air entry and dryness can be given by $D_{R3}=c+3$, where c is a constant (Perfect and Kay, 1995).

Laboratory Methods of Determining Pore Size Distribution

Microscopic Measurements. Thin sections made from appropriately impregnated soil clods are examined under the microscope to determine the size and number of different pores (Burke et al., 1986). Different types of microscopes are used depending on the pore size to be assessed. For example, an optical microscope is used for determining pores of 250 nm, scanning electron microscope for pore size of 10 nm, and transmission electron microscope for size range of 1 nm (Burke et al., 1986).

Water Desorption Method. This method is based on the principle of capillarity. The capillary rise depends on the forces of surface tension and the contact angle between the solid and the liquid. Surface tension (γ) of a water is the difference in pressure at the air-water interface, due to the cohesive forces created by the like molecule sticking together within the bulk volume and creating a greater internal pressure under the liquid surface than above it. Surface tension has the dimension of force per unit length (dynes/cm). The force of surface tension also exists between a solid and air (γ_{ra}) compared with that of

water and air (γ_{wa}), and solid and water (γ_{sw}). As the solid is immersed in water, there are interfacial forces due to adhesion. The work (W_{sw} in ergs or joules) to separate the solid from water depends on the surface tensions and the interfacial area (A_s) and is given by Eq. (5.1).

$$\frac{W_{sw}}{A_s} = \gamma_{sa} + \gamma_{wa} - \gamma_{sw} \quad (5.1)$$

The interface between the solid and water forms a definite angle, or the angle of contact [Eq. (5.2)].

$$\cos \alpha = \frac{\gamma_{sa} - \gamma_{sw}}{\gamma_{wa}} \quad (5.2)$$

This method is based on the assumption that pores in a soil are a bundle of rigid capillaries. The height of rise of water in a capillary tube depends on the surface tension of the wetting liquid with the surface, and the diameter of the tube. Assume that a liquid has risen to height h in the capillary tube shown in Fig. 5.2. At steady state, when the liquid has stopped rising, the net force acting on the meniscus is zero. The downward force ($F\downarrow$) is the gravitational pull [Eq. (5.3)].

$$F\downarrow = \pi r^2 h \rho_1 g \quad (5.3)$$

where r is the radius of the capillary, h is the height of rise of liquid, ρ_1 is the density of the liquid, and g is the acceleration due to gravity. The upward force ($F\uparrow$) is due to the surface tension [Eq. (5.4)].

$$F\uparrow = 2\pi r \gamma \cos \alpha \quad (5.4)$$

where γ is the surface tension of the liquid against the wetting surface (in this case glass) and α is the contact angle for units of surface tension of H_2O and Hg at different temperatures and against a range of solid surfaces.

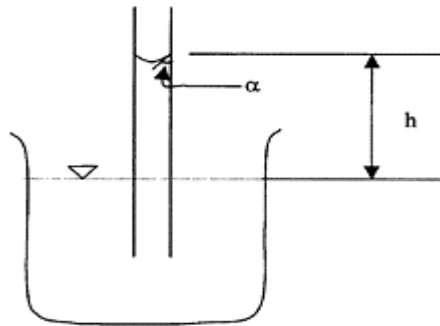


FIGURE 5.2 Capillary rise of water to height h in a glass tube.

At steady state, $F_{\downarrow} = F_{\uparrow}$

$$\therefore \pi r^2 h \rho_l g = 2\pi r \gamma \cos \alpha \quad (5.5)$$

$$h = \frac{2\gamma \cos \alpha}{r \rho_l g} \quad (5.6)$$

$$r = \frac{2\gamma \cos \alpha}{h \rho_l g} \quad (5.7)$$

Assuming that the wetting liquid is H_2O at $20^\circ C$, then γ is 72.75 dynes/cm or g/s^2 , ρ_l is 0.9982 g/cm^3 , g is 980 cm/s^2 , and α is 0 and $\cos 0$ is one. Substituting these values and rearranging Eq. (5.4) to solve for r leads to:

$$r = \frac{2(72.75) \text{ g}}{h} \cdot \frac{\text{cm}^3}{\text{s}^2} \cdot \frac{\text{s}^2}{0.9982 \text{ g} \cdot 980 \text{ cm}} = \frac{0.15}{h} \text{ cm}, \quad \text{and} \quad h = 0.15/r \text{ cm}$$

Being a polar liquid, water reacts with soil and a nonreactive substance is used instead, i.e., Hg.

Example 5.1

Calculate size of the pores corresponding to a capillary height of water of 10 cm, 100 cm, 1000 cm, and 10,000 cm at $20^\circ C$.

Solution

Using Eq. (5.7) at $20^\circ C$, pore radius for corresponding capillary height is:

$$10 \text{ cm} = \frac{0.15}{10} \text{ cm} = 1.5 \times 10^{-2} \text{ cm}$$

$$100 \text{ cm} = 0.15 \times 10^{-2} \text{ cm} = 1.5 \times 10^{-3} \text{ cm}$$

$$1000 \text{ cm} = 0.15 \times 10^{-3} \text{ cm} = 1.5 \times 10^{-4} \text{ cm}$$

$$10,000 \text{ cm} = 0.15 \times 10^{-4} \text{ cm} = 1.5 \times 10^{-5} \text{ cm}$$

Mercury Intrusion Method. The mercury intrusion technique is similar to the water desorption method based on the capillary rise. This method is often used for fine pores ranging in size from 10 nm to 100 μm (Danielson and Sutherland, 1986). Because Hg does not wet the soil (and the contact angle is 140°), positive pressure has to be used to inject Hg into the soil pores. A principal advantage of the mercury injection technique lies in its non-wettability. Therefore, pore size does not shrink due to swelling.

In this method, the soil sample is dried, evacuated, and inundated in Hg and pressure is applied at discrete steps. The volume of pores at each pressure step is related to the diminution of Hg. Hg is a non-wetting fluid, therefore, the contact angle is $>90^\circ$. The

pressure required to force Hg into soil pores is a function of contact angle, size, and geometry of pore and surface tension. The equivalent radii of smallest pores (r_p) can be calculated by the following equation:

$$r_p = \frac{-2\gamma \cos \theta}{P} \quad (5.8)$$

where γ is surface tension of Hg (J/m^2), θ is the contact angle of Hg on soil, and P is absolute pressure (N/m^2). The negative sign used in the above equation cancels the negative value of $\cos \theta$ and provides a positive value of r_p . The r_p values calculated by this method for each pressure steps are consistently lower than the actual and, therefore, multiplied by a correction factor of 1.31. For a detailed description on the above methods, readers are referred to Sills et al. (1973a; b), and Danielson and Sutherland (1986).

Nitrogen Sorption. Similar to Hg, other nonpolar liquids also do not react with clay. Soil sample must be dried, however, prior to using any nonpolar liquid. Freeze-drying is preferred because it does not cause shrinkage. The N-sorption is done on freeze-dried soil cooled to a low temperature of 78 K when a liquid-gas interface is formed for N. Equations (5.5) to (5.7) can be used for N for computing r (Aylmore and Quirk, 1967). A comparison between mercury injection and nitrogen sorption for evaluating pore size distribution is shown by Sills et al. (1973a).

PROBLEMS

1. Calculate the height of capillary rise in a soil pore of 50 μm inner diameter in winter (5°C), spring (20°C), summer (30°C), and the tropics (40°C).
2. Compute the pressure difference at the air-water interface in Question 1 above.
3. Consider the following equation of the height of capillary rise $r=2\gamma/(\rho gh)$, where γ and ρ refer to the surface tension and density of the fluid, respectively. Calculate the difference in the height of the capillary rise in 20 μm diameter pore for (a) water and (b) alcohol at 20°C .
4. Compute the maximum size of the pores that will retain water in soil corresponding to suction (capillary height) of 330 cm and 15,000 cm of water.
5. A soil has a perched water table at 1-m below the surface. Predominant soil capillary pores have an ECD of 0.05 mm. If corn roots penetrate to 30 cm depth, can corn survive a prolonged drought without severe decline in yield?
6. What is the principal of mercury-injection porosity meter? Why is mercury injected under pressure?
7. Determine ECD corresponding to Hg injection pressure of 10,000 and 1,000 cm.

REFERENCES

- Anderson, S.H., R.L.Peyton and C.J.Gantzer. 1990. Evaluation of constructed and natural soil macropores using x-ray computed tomography. *Geoderma* 46: 13–29.
- Aylmore, L.A.G. and J.P.Quirk. 1967. The micropore size distribution of clay mineral systems. *J. Soil Sci.* 18:1–17.
- Brewer, R. 1964. *Fabric and Mineral Analysis of Soils*, Wiley, New York.
- Carter, M.R. and B.C.Ball. 1993. Soil porosity. In M.R. Carter (ed) “Soil Sampling and Methods of Analysis”, Lewis Publishers, Boca Raton, FL: 581–588.
- Childs, E.C. 1968. The Physical basis of Soil Water Phenomena, Wiley, London.
- Danielson, R.E. and P.L.Sutherland. 1986. Porosity. In A. Klute (ed) “Methods of Soil Analysis” Part 1, American Society of Agronomy, Monograph 9, Madison, WIP 443–461.
- Derdour, H.D.A.Angers and M.R. Laverdiere. 1993. Caracterisation de l'espace poral d'un sol argileux: effets de res constituants et du travail du sol. *Can. J. Soil Sci.* 73:299–307.
- Douglas, J.T. 1986. Macroporosity and permeability of some cores from England and France. *Geoderma* 37:221–231.
- Ehlers, W. 1975. Observations on earthworm channels and information on tilled and untilled loess soils. *Soil Sci.* 119:242–249.
- Flury, M. and H.Fluehler. 1995a. Modeling solute transport in soils by diffusionlimited aggregation. Basic concepts and application to conservative solutes. *Water Resources Res.* 31:2443–2452.
- Flury, M. and H.Fluehler. 1995b. Tracer characteristics of Brilliant Blue FCF. *Soil Sci. Soc. Am. J.* 59:22–27.
- Greenland, D.J. 1977. Soil damage by intensive arable cultivation: temporary or permanent? *Phil. Trans. Roy Soc. London, B*, 281:193–208.
- Grevers, M.C.J. and E.De Jong. 1990. The characterization of soil macroporosity of a clay soil under ten grasses using image analysis. *Can. J. Soil Sci.* 70:93–103.
- Hamblin, A. 1985. The influence of soil structure on water movement, crop root growth, and water uptake. *Adv. Agron.* 38:95–158.
- IUPAC, 1972. *Manual of Symbols and Terminology*, International Union of Pure and Applied Chemistry, London.
- Johnson, W.M., J.E.McClelland, S.B.McCaleb, R.Ulrich, W.G.Harper, and T.B.Hutchings. 1960. Classification and description of soil pores. *Soil Sci.* 89:319–321.
- Jongierius, A. 1957. *Morphological Investigations of Soil Structure*, Bodemkundige studiea, No. 2, Meded. van der Sticking Bodemkartiering, Wageningen.
- Kay, B.D. 1990. Rates of change in soil structure under difficult cropping systems. *Adv. Soil Sci.* 12:1–52.
- Kay, B.D. 1998. Soil structure and organic carbon: A review. In: R. Lal, J.M. Kimble, R.F.Follett and B.A.Stewart (eds) “Soil Processes and the Carbon Cycle.” CRC/Lewis Publishers, Boca Raton, FL: 169–197.
- Lepiec, J., R.Hatano, A.Slowinska-Jurkiewicz. 1998. The fractal dimension of pore distribution patterns in variously-compacted soils. *Soil & Tillage Res.* 47:61–66.
- Luxmoore, R. 1981. Micro-, meso-, and macroporosity of soil. *Soil Sci. Soc. Am. J.* 45:671–672.
- Manegold, 1957. Quoted by A.E. Scheidegger (1957) “The Physics of Flow Through Porous Media.” Univ. of Toronto Press, Toronto, Canada.
- McIntyre, D. 1974. Porespace and aeration determinations. In: J. Loveday (ed) “Methods for Analysis of Irrigated Soils.” Commonwealth Agric. Bureau, Farnham Royal.
- Perfect, E. and B.D.Kay. 1995. Application of fractals in soil and tillage research: a review. *Soil & Till. Res.* 36:1–20.
- Ross, P.J., J.Williams and K.L.Bristow. 1991. Equation for extending water retention curves to dryness. *Soil Sci. Soc. Am. J.* 55:923–927.

- Sills, I.D., L.A.G.Aylmore and J.P.Quirk. 1973a. A comparison between mercury injection and nitrogen sorption as methods of determining pore size distribution. *Soil Sci. Soc. Amer. Proc.* 37:535–537.
- Sills, I.D., L.A.G.Aylmore and J.P.Quirk. 1973b. An analysis of pore size in illite– kaolinite mixtures. *J. Soil Sci.* 24:480–490.
- Smart, P. 1975. Soil micro structure, *Soil Sci.* 119:385–393.
- Soil Survey Division Staff, 1990. *Soil Survey Manual*. Natural Resource Conservation Service, Washington, D.C.
- Tyler, S.W. and S.W.Wheatcraft. 1990. Fractal processes in soil water retention. *Water Res. Res.* 26:1047–1054.

6

Manifestations of Soil Structure

The dynamic of soil structure has numerous agronomic, economic, and ecological implications. Thus, sustainable management of natural resources requires optimization of soil structural characteristics. Structural degradation and decline in aggregation of structured soils lead to soil dispersion, crusting, compaction, formation of pans, accelerated soil erosion, and emission of CO₂ and other greenhouse gases into the atmosphere (Fig. 6.1). These ramifications can have a drastic impact on plant growth and net primary productivity, hydrologic cycle, water quality, elemental cycling, and emission of trace gases (Fig. 6.2). The interactive effects of soil processes, soil properties, plant growth, and environment can adversely impact ecosystem functions (Fig. 6.3). The latter includes biomass production, purification of water, detoxification of natural and anthropogenic pollutants, restoration and resilience of ecosystems, and cycling of elements.

6.1 CRUSTING AND SURFACE SEAL FORMATION

Crusting is a soil surface phenomena caused by susceptibility of aggregates at the soil-air interface to disruptive forces of climatic elements and perturbations caused by agricultural practices (e.g., tillage and traffic). Slaking, deflocculation, or dispersion of aggregates on rapid wetting or submersion in water, is attributed to numerous factors including the effect of entrapped air, predominance of Na⁺ on the exchange complex, and weak aggregate strength caused by low level of soil organic matter content and weak ionic bonds. These factors and processes governing them are discussed by Sumner and Stewart (1992). Dispersion, reorientation of dispersed particles, drying, and desiccation, lead to formation of a thin crust on the soil surface. Soil crust or surface seal, therefore, refers to the thin dense layer on the soil surface characterized by low porosity, high density, and low permeability to air and water.

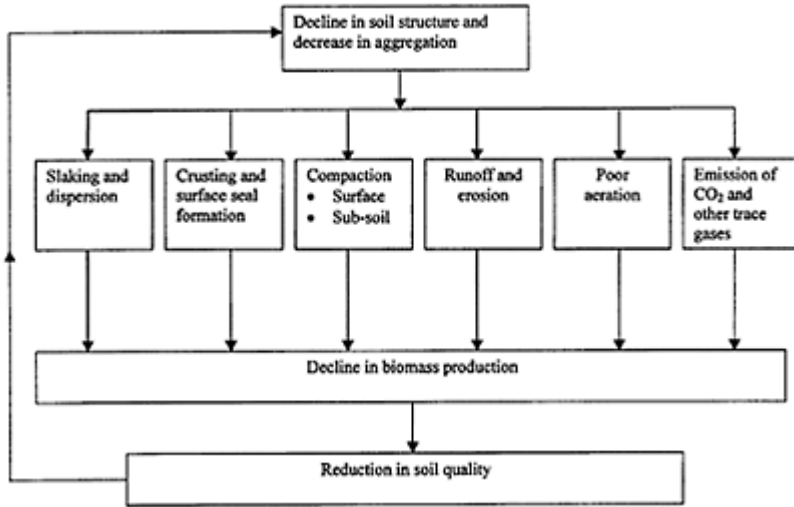


FIGURE 6.1 Impact of decline in soil structure on soil physical quality.

6.1.1 Types of Crusts

There are three principal categories of crust: chemical crusts, biological crusts, and physical crusts (Figs. 6.4a;b;c). *Chemical crusts* are formed due to salt incrustations on soil surface in arid and semi-arid regions. *Biological* or *microbiotic crusts* are primarily formed by algal growth. Ponded water on surface of slowly permeable soils in arid and semi-arid tropics lead to formation of algal crusts. Such crusts are extremely hydrophobic, and drastically reduce the rate of water infiltration into a soil. *Physical crusts* are formed due to alteration in structural properties of the soil, and may be *structural* or *depositional*.

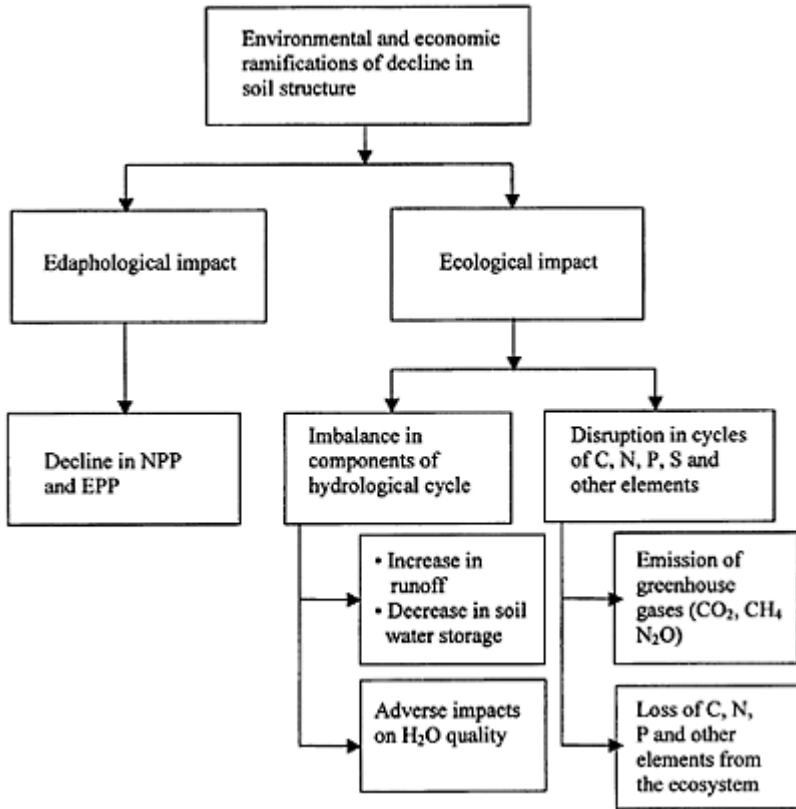


FIGURE 6.2 Economic and environmental ramifications of decline in soil structure (NPP is net primary productivity, and EPP is ecosystem primary productivity).

Structural Crust

Structural crust is formed due to the disruption of aggregates by raindrop impact and physiochemical dispersion of soil clays (McIntyre, 1958a; b). The upper surface of the structural crust, or “skin seal,” has low permeability and is about 1–3 mm thick. Sodic soils, those with high percentage of exchangeable Na⁺ on the exchange complex, are extremely prone to formation of structural crust.

Depositional Crust

Depositional crust is formed by transport and deposition of fine particles by surface flow (Chen et al., 1980). Depositional crusts are thicker than structural crusts, and are formed

wherever suspended fine-textured material in water gets settled. Kinetic energy of raindrops and dispersional properties of soil have no effect on formation of depositional crusts.

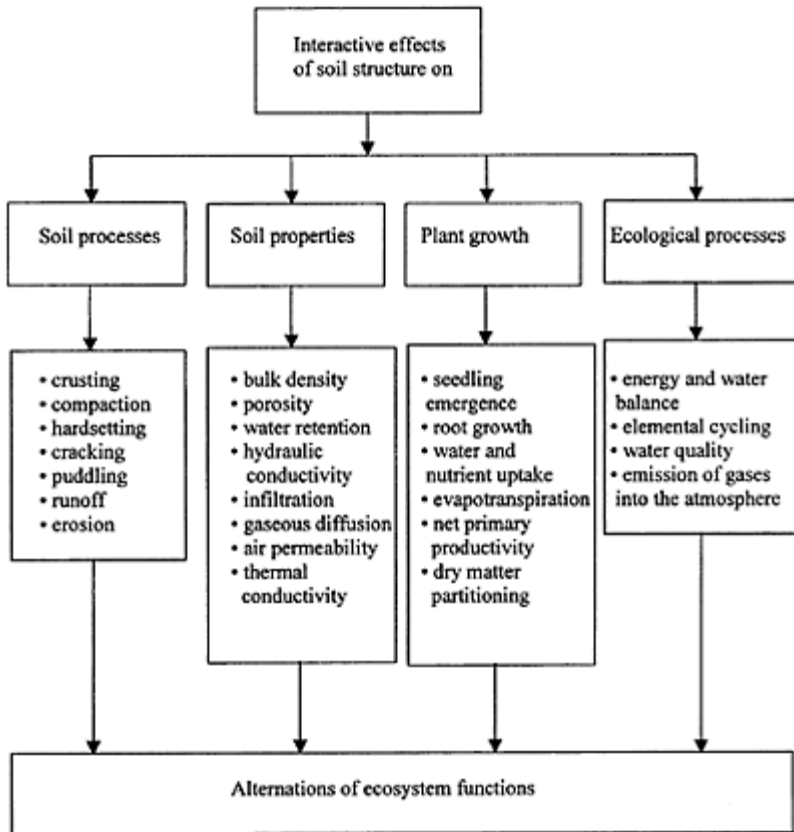


FIGURE 6.3 Effects of soil structure on ecosystem functions.

6.1.2 Factors Affecting Slaking and Deflocculation

There are three principal factors: Kinetic energy of rainfall, soil properties, and anthropogenic factors (for anthropogenic factors, refer to Sec. 6.1.7 in this chapter).

Rainfall Factor

Slaking is principally caused by the kinetic energy of impacting raindrops (McIntyre, 1958b; Shainberg et al., 1989; Bradford and Huang, 1992). The kinetic energy ($E=1/2 mv^2$, where m is the mass of rain per unit area and v is the impact velocity of rain drop) and momentum ($M=mv$) are the primary sources of energy that disrupts an aggregate.

The rate and intensity of crust formation increases with increase in energy of the raindrop impact. The energy of flowing water may also have indirect impact, probably due to its influence on transport and deposition of sediments.

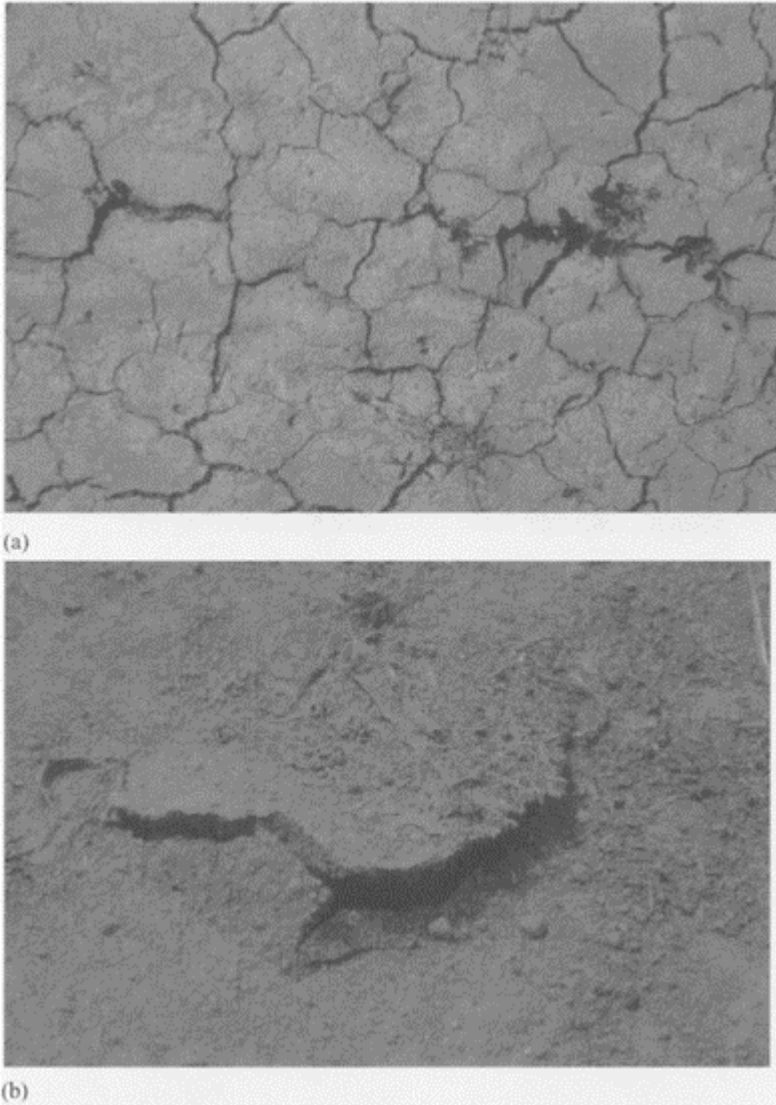


FIGURE 6.4 (a) Silt loam soils with low organic matter content are prone to formation of surface seal or crust, (b) High strength surface seals inhibit