distribution	scale,

TABLE 4.8 Some Indices of Soil Structure Based on Properties Other Than Aggregates

Soil property	Index of soil structure
Porosity	(i) Total porosity *(f_t)* (ii) Pore size distribution (D_{50}) (iii) Aeration porosity *(f_a)*
Soil strength	(i) Penetration resistance (ii) Modulus of rupture (iii) Relative density
Water retention	(i) Plant available water capacity (ii) Least limiting water range
Water transmission	(i) Infiltration capacity (ii) Profile hydraulic conductivity (iii) Soil drainage
Aeration	(i) Oxygen diffusion rate (ii) Diffusion coefficient

contained in a cylinder 5 cm diameter and 40 cm deep, and *b* is actual silt+clay content determined by routine mechanical analysis with disper-sion agent.

Aggregated (Silt+Clay) (Middleton, 1930)

This index is computed from the analysis done for the dispersion ratio, and is the difference between actual (silt+clay) and the percent suspension determined without dispersion.

Clay Ratio (Bouyoucos, 1935)

This refers to the ratio between sand and silt+clay. It is a measure of the amount of binding material and has also been called "mechanical ratio" (Boyd, 1922).

Colloid Content–Moisture Equivalent Ratio (Middleton, 1930)

This ratio is used as an index of soil erodibility. Soil colloid content comprises clay plus organic matter expressed in percent, and moisture equivalent is the soil moisture content when soil is subjected to a centrifugal force equivalent to 1000 G. Nonerodible soils usually have a ratio >1.5 and erodible soils <1.5.

Erosion Ratio (Middleton, 1930)

The erosion ratio is calculated as per Eq. (4.12).

$$\text{Erosion ratio} = \frac{\text{Dispersion ratio}}{\text{Colloid content/moisture equivalent}} \quad (4.12)$$

For this ratio a value of 10 is thought to be a boundary between erodible and nonerodible soils.

Silica: Sesquioxide Ratio

This ratio is based on the relative proportion of cementing agents (R_2O_3) in comparison with the material to be cemented (SiO_2). This ratio is also an index of soil erodibility and may range from <1 for nonerodible soils to as high as 9 for erodible soils.

Surface Aggregation Ratio

Anderson (1954) proposed the ratio between the total surface area of par-ticles larger than 0.05 mm diameter and the quantity of aggregated silt+clay content.

Index of Resistance *(I_r)*

Chorley (1959) proposed an index of resistance against erosion by water as per Eq. (4.13).

$$I_r = \frac{\rho_b \times D_r}{w} \quad (4.13)$$

where ρ_b is soil bulk density, D_r is the range of particle size, and w is soil moisture content.

Index of Erodibility *(I_e)*

Chorley combined I_r with permeability to obtain I_e [(Eq. 4.14)].

$$I_e=(I_r \times k)^{-1} \quad (4.14)$$

where k is soil permeability (see Chapter 12 on soil water movement).

Index of Structural Stability *(I_s)*

Kay et al (1988) proposed an index of structural stability based on the rate of change in the level of stabilizing material [Eq. (4.15)].

$$C_i/C_o = (1 - e^{-k_1 T_i}) \quad (4.15)$$

where C is the stabilizing constituent (humic fraction or organo-mineral complexes) representing original (C_0) and final (Ci) concentration, T_i is the time (yr) and k_1 is the rate constant.

Index Based on Texture and Cementing Agents

Henin et al. (1958) proposed an instability index (I_s) based on cementing agents involved in aggregation of tropical soils [Eq. (4.16)].

$$I_s = \frac{(A + LF)_{\max}}{\frac{1}{3}Ag - 0.9SG} \qquad (4.16)$$

where $(A+LF)_{max}$ is the maximum amount of dispersed 0–20 mm fraction obtained after three treatments of the initial soil sample: (i) without any pretreatment (air dry), (ii) following immersion in alcohol, and (iii) following immersion in benzene; and Ag refers to the >200 mm aggregates (air, alcohol, and benzene) obtained after shaking (30 manual turnings and wet sieving of the 3 pretreated samples), SG represents the contents of coarse mineral sand (>200 µm), and ($1/3\ Ag-0.9\ SG$) represents mean stable aggregates.

Index of Crusting

FAO (1979) proposed an index of crusting (I_c) based on textural composition and soil organic matter content [Eq. (4.17)].

$$I_c = \frac{1.5S_f + 0.75S_c}{Cl + (10 \times SOM)} \qquad (4.17)$$

where S_f is % fine silt, S_c is % coarse silt, Cl is % clay, and SOM is % soil organic matter content. Obviously, I_c is inversely related to clay and soil organic matter content, and directly to fine and coarse silt content.

Critical Soil Organic Matter Content

Soil organic matter concentration plays a major role in forming and stabilizing aggregates (Dutartre et al., 1993). Pieri (1991) proposed the concept of critical level of soil organic matter concentration for structural stability of tropical soils [Eq. (4.18)].

$$S_t = \frac{(SOM)}{(Clay + silt\ content)} \qquad (4.18)$$

Based on the analysis of about 500 samples from semiarid regions of West Africa, Pierie (1991) proposed the following limits of soil organic matter concentration for characterizing soil structure:

S_t=<5%, loss of soil structure and high susceptibility to erosion
S_t=5 to 7%, unstable structure and risk of soil degradation
S_t=>9%, stable soil structure

Plant Available Water Capacity

Plant available water capacity of the soil (see Chapters 10 and 11) has been used as an index of soil structure. Thomasson (1971) related soil structure to the range of moisture content in which crop growth is optimum. Letey (1985) proposed the "non-limiting water range" or the range of soil water content in which neither O_2 nor water nor soil strength limit crop growth. The concept was further developed by Emerson et al. (1994), da Silva et al. (1994), and da Silva and Kay (1996; 1997) into "least limiting water range" as a characteristic of structural form in relation to plant growth. These methods are rarely used because of the complexity of the procedure and a wide range of parameters involved.

4.7.5 Aggregation and Structural Resiliency

Because of its importance, rather than evaluating aggregation properties per se, it may be prudent and more relevant to assess structural resilience (Kay, 1997). It refers to the ability of soil structure to recover following a major disruption in the aggregation process outlined in Eq. (4.5). The disruption may be caused by alterations in land use, cultivation, or soil management practices that change the composition of cations on the exchange complex, decrease quantity and quality of the humus fraction, and reduce effectiveness of the bio tic factors. Numerous soils exhibit selfmulching properties (Fig. 4.21; Blackmore, 1981; Grant and Blackmore, 1991). In other soils, aggregation is restored only when taken out of cultivation and put under a restorative fallow (Lal, 1994). Inevitably, soils with structural resiliency are better suited for intensive management under different land uses than those that do not possess these characteristics. Structural resiliency depends on numerous factors including soil organic matter content, clay mineralogy, wettability characteristics, and biotic factors. It may be important to evaluate soils according to numerous indices outlined in Tables 4.6 and 4.7, and develop a comprehensive index of structural resiliency.

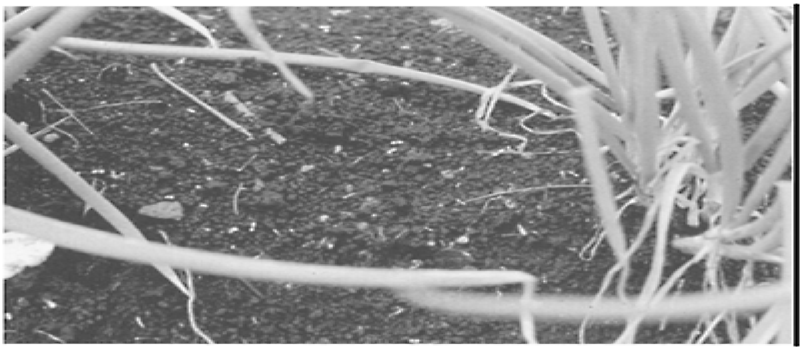

FIGURE 4.21 Surface layer of some vertisols and andisols have self-mulching characteristics with fine- to medium-crumb structure.

4.7.6 Fractal Analyses and Soil Structure

Fractals may describe spatial and temporal systems that may be generated by applying scaling theories using an iterative algorithm (Federer, 1988). These are complex systems at any given scale and therefore, useful for modelling structure in heterogeneous soil. The scaling factors can be unique in a self-similar system and different for each coordinate axis for a self-affine system (Federer, 1988). Spatial fractals are constructed by repeatedly copying a pattern on to the initiator or starting system, or algorithm, which can be accretive, reductive, or mass conserving. For different soil operations, different fractal dimensions and different algorithms are used. Pore size distribution is described by reductive algorithm, whereas, fragmentation and surface irregularity are mostly described by mass-conserving and accretive algorithms (Perfect and Kay, 1995).

The fractal techniques can be used for modelling the structure of heterogeneous soils by quantifying the changes in aggregate size, density and outlines of aggregates, ped shapes, bulk density and pore size distribution. Not all the parameters can be easily assessed, however. The fractal analysis uses the aggregate number-size distribution instead of mass-size distribution determined normally by wet sieving technique. From the known values of aggregate mass-size distribution, bulk density and shape of aggregate in each size fraction, the number-size distribution can be determined by the following equation:

$$N\left(\frac{1}{b^i}\right) = k\left(\frac{1}{b^i}\right)^{-D}; i = 0,1,2,3\ldots\infty \qquad (4.19)$$

where $N(1/b^i)$ is the number of elements of length $1b^{i,}$ k is the number of initiators of unit length, b is a scaling factor greater than 1, and D is the fractal dimension and can be defined as a fractional dimension (noninteger), which determines the space filling capability of generator in the limit $i \to \infty$.

4.8 IMPACT OF DECLINE IN AGGREGATION AND STRUCTURAL DEGRADATION

Reduction or reversal of the aggregation process has far-reaching local, regional, and global impacts on agriculture (Fig. 4.22). Crusting and surface seal formation (local impacts) (Passioura, 1991) are the precursors to surface compaction, low infiltration, and high soil evaporation. Soil slaking and dispersion lead to exposure of C otherwise tied or locked within the aggregate, which accentuates its microbial decomposition and oxidation. These local processes are determined by biophysical factors and processes, e.g., ion exchange, organomineral complexes, wetting-drying, and freeze– thaw cycles. Local processes of runoff and accelerated erosion are combined at regional scale. Runoff and erosional processes on a watershed scale lead to disruption in cycles of H_2O, and exacerbation of aridization and desertification processes with severe global implications. Disruptions in cycles of C and N also lead to emissions of radiatively-active gases

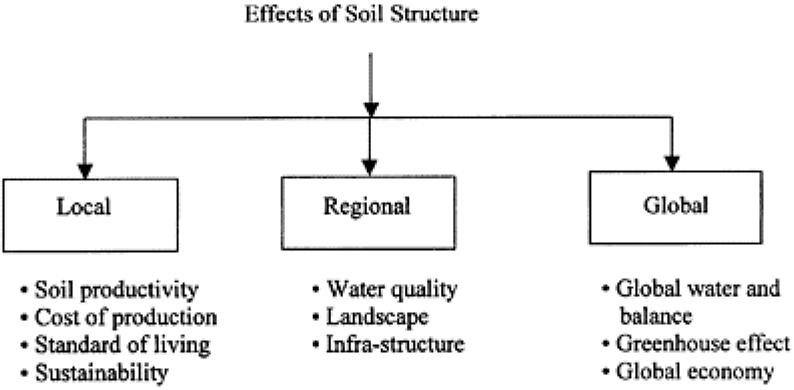

FIGURE 4.22 Local, regional, and global effects of decline in soil structure.

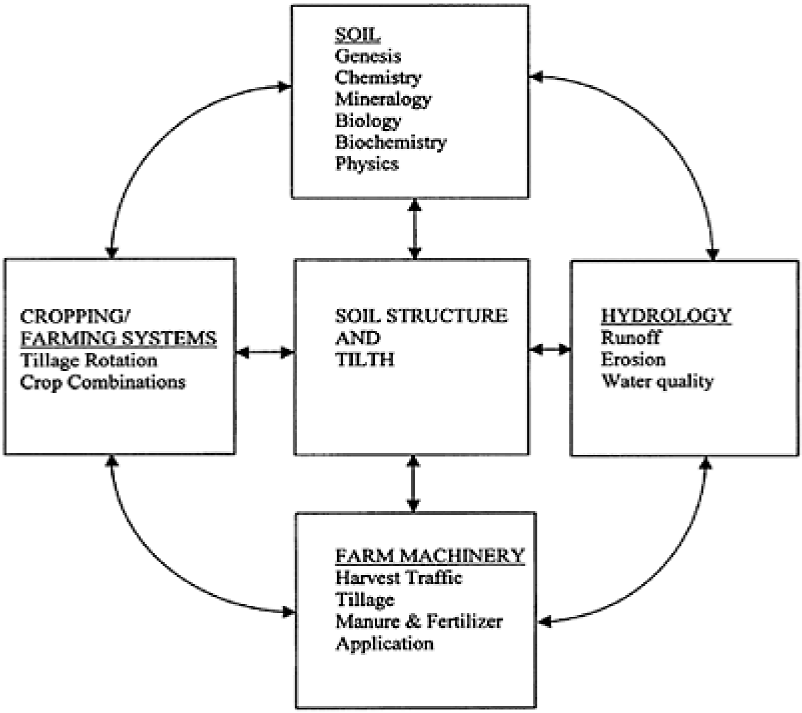

FIGURE 4.23 A multidisciplinary approach to soil structure.

(CO_2, CH_4, CO, N_2O, NO_x) from soil to the atmosphere with attendant risks of the accelerated greenhouse effect (Lal, 1995; 1999; 2001; 2003). At regional and global scales, these processes are driven by socioeconomic and political causes, and policy issues are major considerations. It is because of these interactive effects with numerous impacts that the structure and tilth constitute a central theme of multidisciplinary importance involving soil science, agronomy/plant physiology, engineering, hydrology, and climatology (Fig. 4.23).

4.9 MANAGEMENT OF SOIL STRUCTURE

There are numerous economic and environmental impacts of soil structure (Fig. 4.24), especially those that affect soil quality in relation to productivity

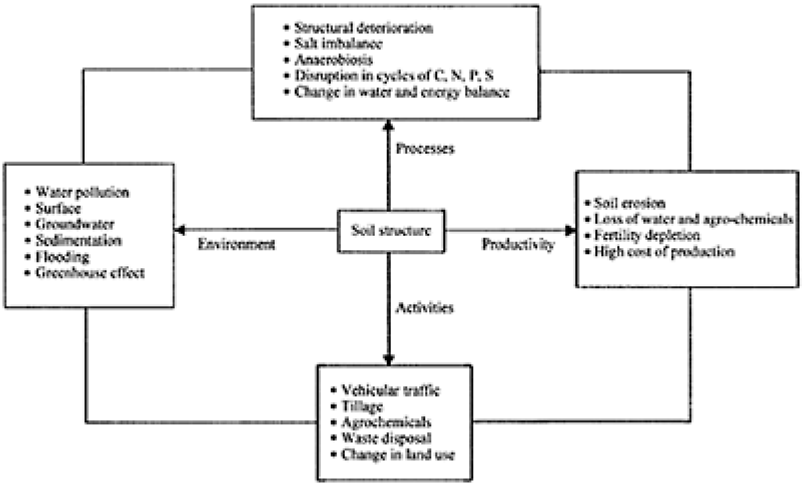

FIGURE 4.24 Economic and environmental impacts of soil structure.

and environmental moderation capacity. Therefore, management of soil structure is crucial to sustainable use of soil and water resources and minimize structural decline of soils (Emerson, 1991). Soil and crop management systems are to be chosen to enhance aggregation and structural stability. For additional readings on this topic, readers are referred to reviews by Baver et al. (1972), Hamblin (1985; 1991), Kay (1990), and Carter and Stewart (1995).

4.9.1 Cropping and Farming Systems

Root systems and canopy cover have an important influence of soil structure. Grasses with their dense and fibrous root system and legumes with their deep tap roots have a profound effect on aggregation characteristics. It is because of these and other differences in legumes and cereals that crop rotations and farming systems have a profound effect on soil structure (Kay et al., 1988). Crops affect structural properties through their impacts on root biomass, amount and rate of water extraction from different depths, total biomass produced, and C:N ratio of the biomass that affects its persistence. From a long-term study in Ohio, Lal et al. (1990) observed that relative aggregation for different rotations was 1.00:1.66:2.1 for corn-oats-meadow, continuous corn, and corn-soybean. The MWD was 1.34 mm for corn-soybean, 1.0 mm for continuous corn, and 0.7 mm for corn-oats-meadow rotation. Perennial forages, both legumes and grasses, improve soil structure (Wilson et al., 1947; Low, 1972; Lal et al., 1979; Lal, 1991). Through their beneficial effects on soil organic carbon (Wilson and Hargrove, 1986; Wilson et al., 1982) and total soil nitrogen contents (Blevins et al., 1990; Camberdella and Corak, 1992). In Ohio, Lal et al., (1997) observed that growing tall fescue and smooth bromegrass for five years increased soil organic carbon content by 18.5%, and total soil nitrogen by 12.5% for 0 to 3 cm depth. Management of the crops and cropping system, use of pasture within a crop rotation, soil surface, and fertility management practices are all important to structural management.

4.9.2 Tillage

Structural effects of tillage depend on the type, frequency, and timing of tillage operation. The antecedent soil moisture content is an important parameter that affects structural properties, because it influences dispersibility of clay. Conservation tillage and mulch farming techniques are beneficial to aggregation and soil structure formation (Lal, 1989; Carter, 1994). Lal et al., (1994) reported that in Ohio, tillage effects on total aggregation and MWD were in the order of no tillage > chisel plowing > moldboard plowing.

4.9.3 Water Management

Drainage of excessively wet soil and irrigation of dry soil may alter aggregation (Collis-George, 1991). The nature and magnitude of effect may depend on soil and environments. In Ohio, Lal and Fausey (1993) observed that the MWD was 2.94 mm for undrained compared with 2.49 mm for drained soil because of decrease in soil organic matter content with drainage. Supplemental irrigation may improve aggregation with good quality water and decrease aggregation with poor quality water containing high proportions of sodium.

4.9.4 Soil Fertility Management and Soil Amendments

Agricultural practices that enhance biomass production have also favorable effects on aggregation and soil structural development. Use of organic manures, compost, and mulches improve aggregation more than chemical fertilizers (Tisdall et al., 1978). Decrease in soil pH due to chemical fertilizers may adversely affect aggregation, especially in soils of low activity clays. Otherwise, use of chemical fertilizers has beneficial effects on aggregation (Emmond, 1971; Hamblin, 1985).

4.9.5 Soil Conditioners

Soil conditioners are synthetic polymers which can be adsorbed by the surface of the clay particles, and alter its relation to water and ions in the solution (see Sec. 4.6.5). One polymer molecule can also link several clay particles through formation of interparticle bonds that facilitate flocculation of a dispersed system or stabilize an existing unstable arrangement of particles. The adsorption of a polymer on clay particles leads to entropy and enthalpy changes due to the change in the state of the molecule in the solution phase to its state in the adsorbed phase, and due to interaction energy involved in the change in the association of soil particle with the polymer molecule. These adsorptive mechanisms have been described by Greenland (1965a; b) and Mortland (1970). The adsorption process is significant when a large net release of enthalpy (ΔH) occurs or the interaction is exothermic. There are two levels of interaction energy that determine the adsorption of polymers on clay surfaces: (i) the net interaction energy E and, (ii) the critical energy E_c. The adsorption process is complete when $E > E_c$. In addition to enthalpy changes, entropy changes may also occur. Restriction of the polymer by interface causes some loss in entropy (AS). Gain in entropy may be due to: (i) liberation of water from the clay surface, (ii) movement of water molecules from or to the polymer, as well as from or to the surface phase, and (iii) changes in configuration of the polymer. There is a wide range of polymers that have been used as soil conditioners. Their effectiveness, however, depends on soil properties, management and climate.

PROBLEMS

1. How does soil structure affect: (a) crop growth, (b) quality of ground water, and (c) air quality?

2. Describe the role of aggregation in soil carbon sequestration, and highlight the mechanism involved.

3. A farmer in Ohio has shifted from conventional tillage to no-till farming. By so doing, soil organic carbon content in the top 1-m depth is increasing at the rate of 0.01% per year. Assuming mean soil bulk density of 1.5 Mg/m3, calculate the rate of carbon sequestration in this 1000 ha farm.

4. Dry and wet-sieving analyses were done on 100 g weight of two soils to get the following results:

	Dry sieving (g)		Wet sieving (g)	
Sieve size (mm)	No-till	Plow till	No-till	Plow till
5–8	10	5	8	4
2–5	15	8	12	10
1–2	15	8	10	8
0.5–1	12	10	10	7

0.25–0.5	8	7	6	5
0.1–0.25	8	6	6	4

Calculate and plot summation curve, percent aggregation > 1 mm, MWD, and GMD. Which soil is prone to wind or water erosion, and why?

Sieve No.	8	10	14	20	28	35	48	65	100	150	200
Opening in mm	2.36	1.65	1.17	0.83	0.59	0.41	0.30	0.21	0.15	0.10	0.075
Soil weight (g) A	28.5	25.0	14.8	12.1	6.3	2.0	3.1	2.0	2.1	1.8	2.3
B	2.3	1.8	2.1	2.0	3.1	2.0	6.3	12.1	14.8	25.0	28.5

5. Calculate "mean weight diameter" and "geometric mean diameter" from the following data. The equivalent oven dry weight=100 g.

6. Plot the above data as a summation curve.

7. A soil has 10% of fine silt, 15% of coarse silt, 40% of clay, 35% sand, and 2.5% soil organic matter content. Compute I_c, S_t, and clay ratio.

8. What is the importance of soil structure to plant growth?

9. Jack (1963) stated that soil structure is as important as photosynthesis. List reasons in justification of this statement.

10. In what ways may the projected global climate change affect soil structure in (a) temperate and (b) tropical climates?

APPENDIX 4.1 SPECIFICATION FOR SIEVE SERIES (SEE ALSO APPENDIX 3.1)

Size of sieve, μ	Sieve number, mesh per inch	Sieve opening, mm	Nominal wire diameter, mm
4000	5	4.000	1.370
2000	10	2.000	0.900
1190	16	1.190	0.650
1000	18	1.000	0.525
840	20	0.840	0.510
500	35	0.500	0.315
250	60	0.250	0.180

210	70	0.210	0.152
177	80	0.177	0.131
149	100	0.149	0.110
74	200	0.074	0.053
53	270	0.053	0.037
37	400	0.037	0.025

REFERENCES

Anderson, H.W. 1954. Suspended sediment discharge as related to stream flow topography, soil and land use. Trans. Am. Geophys. Union 35:268–281.

Angers, D.A. and G.R.Mehuys. 1993. Aggregate stability to water. In M.R. Carter (ed) “Soil Sampling and Methods of Analysis”, Lewis Publishers, Boca Raton, FL: 651–657.

Angers, D.A. and C.Chenu. 1997. Dynamics of soil aggregation and C sequestration. In R.Lal, J.M.Kimble, R.Follett and B.A.Stewart (eds) “Soils and the Carbon Cycle”, CRC, Boca Raton, FL (In press).

Aylmore, L.A.G. and J.P.Quirk. 1971. Domains and quasi-crystalline regions in clay systems. Soil Sci. Soc. Amer. Proc. 35:652–654.

Baver, L.D., W.H.Gardner, and W.R.Gardner. 1972. Soil Physics. Fourth edition. John Wiley & Sons, New York, 498 pp.

Becher, H.H. 1995. Strength distribution in soil aggregates. In: K.H. Hartge and B.A. Stewart (eds) “Soil Structure: Its Development and Functions.” CRC/ Lewis Publishers, Boca Raton, FL: 53–70.

Blackmore, A.V. 1981. Self-mulching soils. In “Soils News”, Aust. Soc. Soil Sci. (July, 1981).

Blevins, R.L., J.H.Herbek, and W.W.Frye. 1990. Legume cover crops as a nitrogen source for no-till corn and grain sorghum. Agron. J. 82:769–772.

Bouyoucos, G.J. 1935. The clay ratio as a criterion of susceptibility of soils to erosion. J. Am. Soc. Agron. 27:738–741.

Boyd, J.R. 1922. Physical properties of sub-grade materials. Am. Soc. Testing Materials Proc. 22:337–355.

Boyd, E.L. Skidmore, and Thompson. 1983. A soil aggregate crushing energy meter. Soil Sci. Soc. Am. J. 47:313–316.

Bradfield, R. 1936. The value and limitation of calcium in soil structure. Am. Soil Survey Assoc. Bull XVII: 31–32.

Brewer, R. 1964. Fabric and Mineral Analysis of Soils. John Wiley & Sons, New York.

Brewer, R. 1976. Fabric and mineral analysis of soils. Krieger Publishing Co., Huntington, N.Y.

Brewer, R. and J.R.Sleeman. 1960. Soil structure and fabric. J. Soil Sci. 11:172–185.

Brewer, R. and A.V.Blackmore. 1956. The effects of entrapped air and optically oriented clay on aggregate breakdown and soil consistence. Aust. J. Appl. Sci. 7:59–68.

Bruce-Okine, E. and R.Lal. 1975. Soil erodibility as determined by the raindrop technique. Soil Sci. 119:149–157.

Bryan, R.K. 1968. The development, use and efficiency of indices of soil erodibility. Geoderma 2:5–26.

Bullock, P., N.Fedoroff, A.Jongerius, G.Stoops, T.Tursina and U.Babel. 1985. Handbook for soil thin section description. Waine Research Publications, Albrighton, Wolverhampton, U.K.

Burke, W., D.Gabriels and J.Buma. 1986. Soil Structure Assessment. A.A. Balkema, Rotterdam, Holland, 92 pp.

Buyanovsky, G.A., M.Aslam, and G.H.Wagoner. 1994. Carbon turnover in soil physical fractions. Soil Sci. Soc. Am. J. 58:1167–1173.

Cambardella, C.A. and S.J.Corak. 1992. Seasonal dynamics of soil organic N and NO_3−N with and without a cover crop. Agronomy Abstract, ASA, Madison, WI, p 251.

Carter, M.R. and B.A.Stewart. 1996. Structure and Organic Matter Storage in Agricultural Soils. Advances in Soil Science, CRC/Lewis Publishers, Boca Raton, FL, 477 pp.

Ceratzki, W. 1956. Zur Wirkung des Frostes auf die Struktur des bodens. Z. Pflanzenernähr, Düngung Bodenk. 72:15–32.

Chaney, K. and R.S.Swift. 1984. The influence of organic matter on aggregate stability in some British soils. J. Soil Sci. 35:223–230.

Chepil, W.S. 1954. The effect of synthetic conditioners on some phases of soil structure and erodibility by wind. Soil Sci. Soc. Am Proc. 18:386–390.

Chorley, R.J. 1959. The geomorphic significance of some Oxford soils. Am. J. Sci. 257:503–515.

Collis-George, N. 1991. Drainage and soil structure: a review. Aust. J. Soil Res. 29:923–933.

Collis-George, N. and R.Lal. 1970. Infiltration into columns of swelling soil as studied by high speed photography. Aust. J. Soil Res. 9:107–116.

Coughlan, K.J., D.McGarry, R.J.Loch, B.Bridge, and G.D.Smith. 1991. Measurement of soil structure: Some practical initiatives. Aust. J. Soil Res. 29:869–889.

Czurda, K.A., S.Ludwig, and R.Schababerle. 1995. Fabric changes in plastic clays by freezing and thawing. In K.H.Hartge and B.A.Stewart (eds) "Soil Structure: Its Development and Functions." CRC/Lewis Publishers, Boca Raton, FL: 71–91.

da Silva, A.P., B.D.Kay, and E.Perfect. 1994. Characterization of the least limiting water range of soils. Soil Sci. Soc. Amer. J. 58:1775–1781.

da Silva, A.P. and B.D.Kay. 1996. Estimating the least limiting water range of soils from properties and management. Soil Sci. Soc. Am. J. 61:877–883.

da Silva, A.P. and B.D.Kay. 1997. Effects of soil, water content variation on the least limiting water range. Soil Sci. Soc. Amer. J. 61:884–888.

de Boodt, M. (ed) 1972. Fundamentals of soil conditioning. Meded., Fak. Landbouwwet. Rijksuniversiteit, Gent.

De Boodt, M. and L.De Leenheer. 1958. Proposition pour *l′* evaluation de la stabilite des aggregates sur le terrain. Proc. International Symp. Soil Structure, Ghent, Belgium: 234–241.

De Leenheer, L. and M.De Boodt. 1959. Determination of aggregate stability by the change in mean weight diameter. Meded. Landb. Gent. 24:290–351.

Douglas, J.T. and M.J.Goss. 1982. Stability and organic matter content of surface soil aggregates under different methods of cultivation and in grasslands. Soil & Till. Res. 2:155–172.

Drees, R. 1992. Optical microscopy and micromorphological terms for thin section descriptions and interpretationsentation. Soil Sci. Soc. Am., Soil Micromorphology Workshop, Oct. 31, 1992, Madison, WI: 6.62.

Dumont, I. (1909). Compt. Rend. Acad. Sci. France 149:1087–1089.

Dutartre, P., F.Bartoli, F.Andreaux, J.M.Portal, and A.Ange. 1993. Influence of content and nature of organic matter on the structure of some sandy soils of West Africa. Geoderma 56:459–478.

Edwards, A.P. and J.M.Bremner. 1967. Microaggregates in soils. J. Soil Sci. 18:64–73.

Ehlers, W. 1975. Observations on earthworm channels and infiltration on tilled and untilled loesssoil. Soil Sci. 119:242–249.

Elliott, E.T. 1986. Aggregate structure and carbon, nitrogen and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J. 50:627–633.

Emerson, E.E., R.C.Foster, J.M.Tisdall, and D.Weissmann. 1994. Carbon content and bulk density of an irrigated Natrixeralf in relation to tree growth and orchard management. Aust. J. Soil Res. 32:939–951.

Emerson, W.W. 1954. The determination of the stability of soil crumbs. J. Soil Sci. 5:235–250.

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.Herbillon (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.