Korean J. Soil Sci. Fert. **42**(1), 58-64(2009)

Article

Relationship between Water Stable Aggregate and Macroporosity in Upland Soils Calculated by Fragmentation Fractal Dimension

Kyung-Hwa Han, Hyun-Jun Cho, Hyup-Sung Lee, Seung-Oh Hur,* and Sang-Keun Ha

National Academy of Agricultural Science, Suwon, 441-707

The objectives of this study were to investigate the aggregate fragmentation in wet-sieving and to evaluate the relationship between the aggregate fragmentation fractal dimension and macro-porosity of upland soils, using three different textural types of soils including Gopyeng series (Fine, Typic Hapludalfs), Gyuam series (Fine silty over coarse silty, Fluvaquentic Eutrudepts), and Jungdong series (Coarse loamy, Typic Udifluvents) located in Gyeonggi province. Undisturbed soil samples with five replicates were seasonally sampled and used for measuring water stable aggregate, macropores, and physico-chemical properties of soils. The aggregate stability in wet-sieving was digitalized as three types of fragmentation fractal dimension (D_f), geometric mean diameter (GMD), and mean weight diameter (MWD). D_f had higher correlation with GMD than with MWD. Seasonal aggregate stability showed the highest values in summer, and decreased in the order of spring and autumn. The macroporosity had higher in topsoil, in autumn, and in ridge, than in plow pan layer, in summer, and in row, respectively. The relationship between D_f and macroporosity, especially more than 99 m, showed high correlation only in soils with D_f less than 3.1, which means more aggregated soils compared to soils with D_f more than 3.1. Besides, in the soils with the fractal dimension less than 3.1, the power function relation between saturated hydraulic conductivity and macroporosity more than 99 m had relatively high determinant coefficient, and vice versa. Therefore, it could be thought that fragmentation fractal dimension is available for confirming macroporosity induced from aggregation.

Key words : Water stable aggregate, Fragmentation fractal dimension, Mean weight diameter, Geometric mean diameter, Macroporosity, Saturated hydraulic conductivity

Introduction

Soil structure is a key controller of the distribution, flow, and retention of water, solutes. gases and biota in agricultural and natural ecosystems (McLaren and Cameron. 1996; Kay, 1989; White, 1985). Especially, inter-aggregate pores in soils can act more rapid water flow-paths than intra-aggregate pores, which induces the preferential flow of water and solutes such as nitrate and successively more severe impact on environmental quality such as ground water pollution (Marshall, 1959; McDonald, 1967; Mosley, 1979; White, 1985). Observation for soil structure has been mainly accomplished through measuring stability and size distribution of aggregate (Dalal and Bridge, 1996). By the way, Young et al. (2001) reported that an investigation of discrete aggregates or distribution of aggregates does not offer any spatial information. Functional traits of soil structure, at all scales, rely on the connectivity, tortuosity and the heterogeneity of pore space in 3D. Their measurement, however, is time-consuming and expensive, as well as difficult to quantify it. On the contrary, the measurement of aggregate stability in wet-sieving is relatively easy and cost-saving, but very arbitrary depending on initial aggregate size and experimental condition. Nevertheless, if the soil has a certain structure, aggregate stability and macropore will simultaneously exist and have some relationship between each other.

Recently, the application of fractal theory on aggregate stability test made it possible to quantify as the process-based indices, being independent of initial aggregate size (Crawford et al., 2000; Perfect et al., 1992; Perrier and Bird, 2003). Fragmentation of aggregate in wet-sieving leads to a distribution of fragment sizes that follow the cumulative form of power function. The fractal

---

Received : January 17. 2009 Accepted : February 10. 2009

*Corresponding author: Phone : +822900336,
E-mail : sohur@rda.go.kr

dimension is a characteristic property of the number-size distribution of fragments as a mass of material is broke down. According to the model proposed by Turcotte (1986), the number-size distribution of fragments is given by $N_i = cx_i^{-D_f}$, where N_i is the cumulative number of fragments in the number-size distribution, obtaining subsequent to fragmentation, up to the *i*th size class, x_i is the mean size of the objects in the *i*th class, c is a constant, and D is fractal dimension. In practice, size distribution data for soil aggregate fragmentation is usually obtained on a mass-size basis. Assuming scale-invariant aggregate bulk density and shape factor s, Perfect et al. (1992) derived the following equation for the estimation of D from mass-size distribution data.

$$\sum_{x=x_{max}}^{x=\overline{x_i}} [\, m_i/x_i^3 \,] = kx_i^{-D_f}$$

In above equation, m_i is oven-dry mass of aggregates and D_f is independent of the geometry and of fragments and k=c for cubic objects. For objects other than cubes, k=c s.

The objectives of this study were to investigate the aggregate fragmentation in wet-sieving and to evaluate the relationship between the aggregate fragmentation fractal dimension and macro-porosity of upland soils.

Materials and Methods

Soil sampling Soil sampling sites with different textural types were selected as Table 1, including U1 (Gopyeong, Fine, Typic Hapludalfs), U2 (Gyuam, Fine silty over coarse silty, Fluvaquentic Eutrudepts), and U3 (Jungdong, Coarse loamy, Typic Udifluvents) located in Gyeonggi province. Undisturbed soil samples with five replicates were sampled at soil surface with block type, topsoil and plow pan layer with 3 inches cores, as shown in figure 1 and table 2.

Fractal theory A fractal object appears morphologically the same, regardless of the scale of observation. Mandelbrot (1993) describes fractals as "shapes whose roughness and fragmentation neither tend to vanish, nor fluctuate up and down, but remain essentially unchanged as one zooms in continually and examination is refined". This is known as scale invariance or scaling. Although natural objects are not fractals in the strict mathematical sense, they often have similar features over a range of scales.

The soil fragmentation mechanism such as water stability of aggregate can be described as fractals, *i.e.*, scale-invariant and power law distribution, when zones of weakness exist at all scales.

Table 1. Description of study sites.

Site	Soil series (Soil Taxonomy)	Location	Crop
U1	Gopyeong (Fine, Typic Hapludalfs)	Suwon, Gyeonggi	Corn
U2	Gyuam (Fine silty over coarse silty, Fluvaquentic Eutrudepts)	Icheon, Gyeonggi	Sesame
U3	Jungdong (Coarse loamy, Typic Udifluvents)	Suwon, Gyeonggi	Red pepper

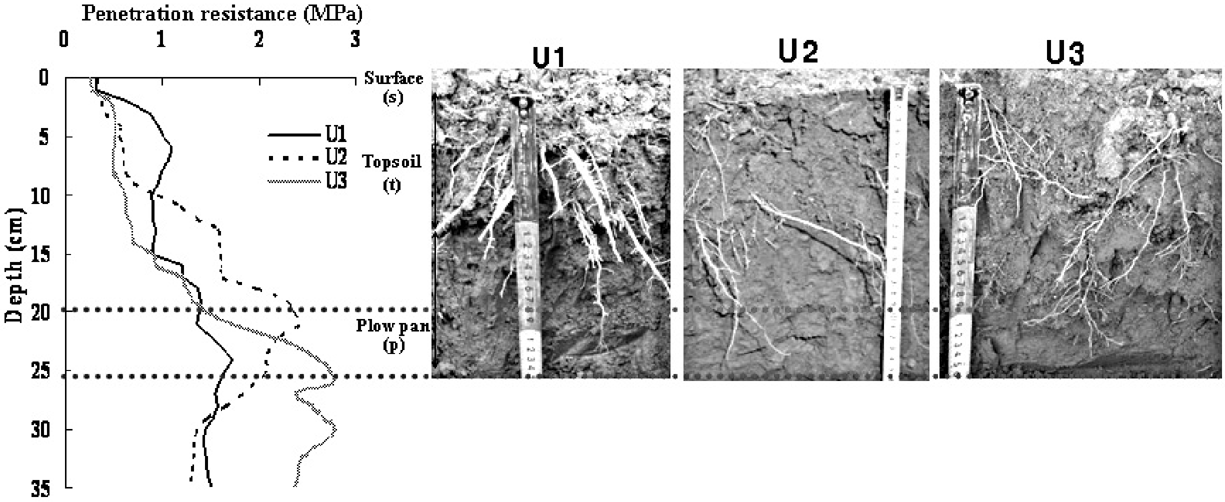

Fig. 1. Discrimination between topsoil and plow pan layer and sampling depths of soils.

Table 2. Soil particle distribution in study sites on the basis of USDA classification.

Site		Sand (%)						Silt (%)	Clay (%)	Texture
		Very coarse	Coarse	Medium	Fine	Very fine	Total			
U1	topsoil	2.2	4.0	2.8	1.8	1.8	12.6	55.9	31.5	SiCL
	plow pan	0.6	1.6	1.8	1.6	2.2	7.8	53.5	38.7	SiCL
U2	topsoil	3.8	8.0	8.8	8.2	9.0	37.8	46.7	15.5	L
	plow pan	0.4	1.0	1.6	4.2	9.5	16.7	66.1	17.2	SiL
U3	topsoil	3.6	12.8	25.6	20.0	8.3	70.3	23.7	6.0	SL
	plow pan	1.0	5.6	34.4	27.6	11.9	80.5	13.5	6.0	LS

Water stable aggregate measurement Aggregate fragmentation in wet-sieving was used with Yoder's sieve shaker (Daiki, Japan), following the method of Rasiah et al. (1995). After a set with 2, 1, 0.5, 0.25 mm sieves was set in the shaker, 10 g air-dry aggregate with diameter 2~4 mm put into the upmost sieve and was saturated with water for five minutes. After up and down shaking for 10 minutes, the sieve with aggregate was dried and weighed. The sand correction was done with sieving, drying and weighing after dispersing the aggregate with 10 mL of 5% sodium hexametaphosphate (Kemper and Koch, 1966; USDA, 1999). Corrected aggregate mass in each sieve was used in calculating aggregate stability indices such as mean weight diameter and geometric mean diameter and fragmentation fractal dimension.

The calculation of water stable aggregates The aggregate stability in wet-sieving was digitalized as three types of fragmentation fractal dimension (D_f), geometric mean diameter (GMD), and mean weight diameter (MWD).

- Mean weight diameter (MWD)

$$MWD = \sum_{i=1}^{n} x_i w_i \qquad (1)$$

where x_i and w_i indicate the mean diameter of each size fraction and the proportion of total sample weight, occurring in the corresponding size fraction, respectively.

- Geometric mean diameter (GMD)

$$GMD = exp\ (\sum_{i=1}^{n} w_i \log x_i \ / \sum_{i=1}^{n} w_i) \qquad (2)$$

- Fragmentation fractal dimension (Df)

$$\sum_{x=x_{max}}^{x=\overline{x_i}} [\, w_i/x_i^3 \,] = kx_i^{-D_f} \qquad (3)$$

Hydraulic properties Soil 3 inches cores (diameter, 7.6 cm and height, 7.6 cm) were saturated from the bottom with a 0.01 N $CaCl_2$ solution and were left under conditions for more than 24 h. The saturated hydraulic conductivity Ks of the cores was determined by constant head method or falling head method. And then, retention curves were measured using the intact 3 inches soil samples. Pore water pressures from -5 cm to -100 cm were measured using sand box equipment. Mean pore diameter (dp, μm) at a given soil water tension was estimated from water-retention using the following equation (Danielson and Sutherland, 1986):

$$dp = 4\sigma \times 10^5 / \ pwgh \qquad (4)$$

where is surface tension of water (0.0724 J m^{-2} at 25), w is density of water (1 Mg m^{-3}), g is gravitational acceleration (9.8 N kg^{-1}), and h is the soil water tension expressed in cm of water.

Soil physico-chemical properties Particle size distribution was measured with hydrometer method, organic matter content with Tyurin method (NIAST, 2000), exchangeable cation with 1N NH_4OAc extraction method, pH (H_2O, 1:5) with a pH meter (Orion, USA), EC(1:5) with a EC meter (EcoScan, Japan) as described in Sparks (1996).

Results and Discussion

Fragmentation fractal dimension compared with aggregate stability indices Fragmentation fractal dimensions (D_f) in aggregate wet-sieving of upland topsoil had a range from 2.5 to 3.8, geometric mean diameter (GMD) from 0.9 mm to 1.2 mm, and mean weight diameter (MWD) from 0.1 mm to 1.1mm (fig. 2). Generally, mass fractal dimension is defined as less than 3, but the values of D_f > 3.00 is theoretically possible if the fragmentation process exhibits multifractal behavior (Rasiah et al., 1995). Our result also showed multifractal behavior with the values of D_f > 3.00, which relatively showed low stability in water compared to $D_f < 3.00$.

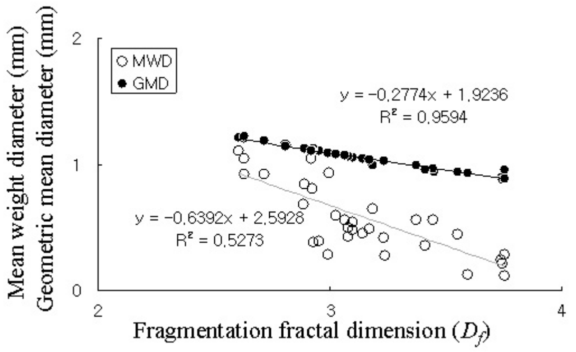

Fig. 2. The relationship between fragmentation fractal dimension (D_f) and water stability indices of aggregate including mean weight diameter (MWD) and geometric mean diameter (GMD).

Fragmentation fractal dimension had higher correlation with geometric mean diameter (GMD) than with mean weight diameter (MWD) (fig. 2). This is probably because GMD is induced from the fragment distribution using exponential function, similar to power function. GMD and MWD had a dimension, length (mm), depending on sizes of chosen aggregate and sieve. On the contrary, D_f has no-dimensional process-based property, and thereby could relatively reduce the error induced from chosen aggregate size and pre-treatment. Therefore, it could be thought that D_f would be relatively proper as the general characterization of the aggregate stability in wet-sieving rather than GMD and MWD.

Aggregate stability and its seasonal variation in upland soils Aggregate stability in different soil layers was shown in fig. 3. Soil surface and topsoil layer had similar fragmentation fractal dimension (D_f), but the plow pan layer had higher values. The higher values of D_f means lower water stability of aggregate, because it has more fragments. The D_f values of plow pan layer were near 4, and thereby most of aggregates fragmented in wet-sieving. This is probably due to low organic matter content and soil compaction induced from agro-machinery work such as tillage (Kay, 1989). U2, having more silt content, had lower aggregate stability in wet-sieving, compared to other soils.

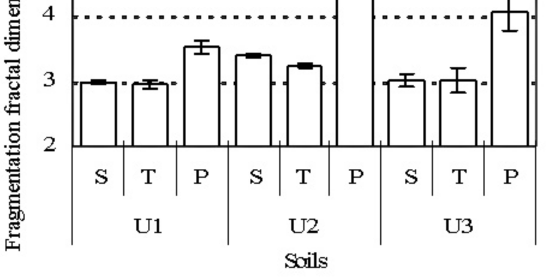

Fig. 3. Water stability of aggregate as affected by different soil layers at study sites; s, t, and p indicate surface(depth 0-5cm), topsoil, and plow pan, respectively. Sampled at March, 31.

Seasonal aggregate stability had highest in summer, and decreased in the order of spring and autumn, shown in D_f and GMD (fig. 4). In case of U2 soil, MWD, unlike D_f and GMD using geometric or power functional calculation, had highest in spring, and decreased in the order of summer and autumn. This indicated that same measurement data could result in different stabilities with different indices. In other words, the difference is probably because the application of power function or geometric mean is focused on fragmentation process rather than arithmetic calculation.

In summer, soil biota including plant root and microorganism have high activity, and so enhance aggregation (Tisdall and Oades, 1982; Oades, 1984: Six et al., 2004). Spring is relatively dry season in Korea. Drier soil can result in more shrinking and hardening of clay, as well as enhancing water-repellency of hydrophobic group in organic matter, which can promote water stability of aggregate (Kay, 1989). On the other hand, in autumn season, biological activity in soils decreases with decreasing temperature, and then aggregate stability in wet-sieving could decrease together (Bronick and Lal, 2005).

Aggregate stability can change with different soil physico-chemical properties, including soil organic matter and exchangeable cation content (Bronick and Lal, 2005; Han et al., 2007). Figure 4 shows the seasonal changes of soil physico-chemical properties. pH and organic carbon content were generally higher values in summer than other seasons, whereas the exchangeable cation content were different with different soils. The seasonal change of physico-chemical properties had no significant effect on aggregate stability. U1 soil with high clay content, relatively had low organic carbon and high exchangeable Ca and Mg content. In spite of the low clay content, U3 soils had relatively high aggregate stability, which is probably due to high exchangeable cation content. U2 soil with high silt content had lowest aggregate stability of three soils regardless of season.

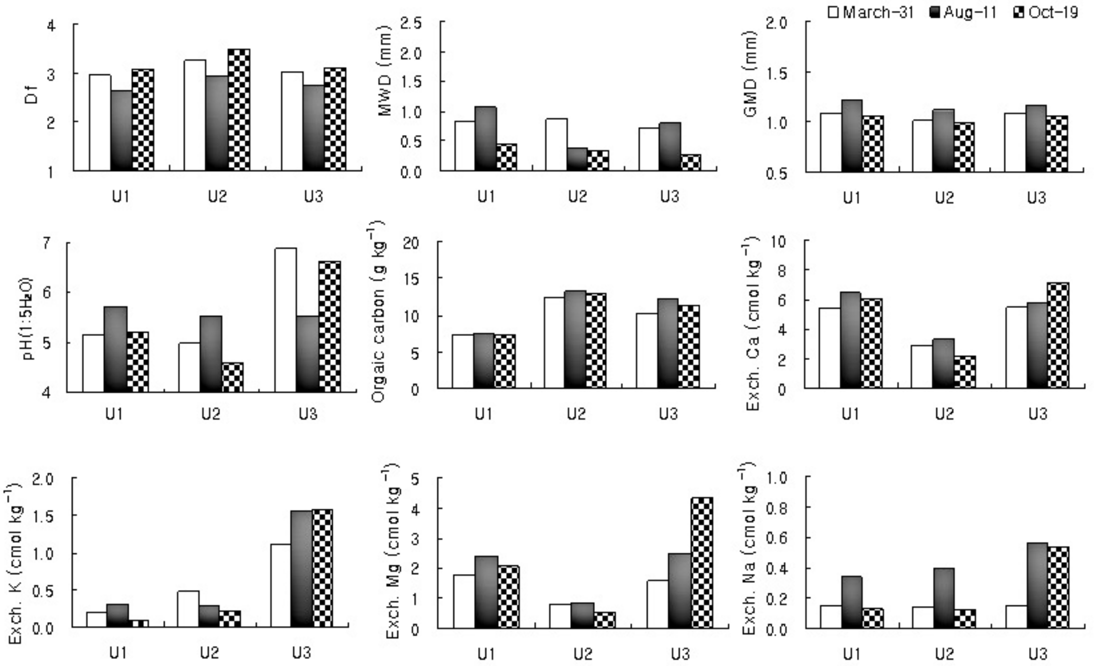

Fig. 4. Temporal variation of water stability of aggregate and soil properties including organic carbon content, pH, and exchangeable cations; D_f, MWD, and GMD indicate fragmentation fractal dimension, mean weight diameter, and geometric mean diameter, respectively.

Macroporosity and its seasonal variation in upland soils The macro-pore size distributions in soils, in summer and autumn, were shown in fig. 5. Upland cultivation commonly has a raised ridge with crop planting point, and thereby ridge and row has different soil structure. Overall, the macro-porosity had higher in topsoil, in autumn, and in ridge, than in plow pan layer, in summer, and row, respectively. Especially, the macroporosity more than 99 m had higher difference than other size groups. The macroporosity more than 296 m was higher in U1 soil with relatively high clay content than in other soils. The porosity between 296 m and 99 m was higher U2 and U3. U3 soil had relatively high porosity between 99 m and 30 m.

Summer in Korea is rainy season. Impact of rain drops on soil surfaces could cause compacting soils, and successively saturation and drainage of water enhance the soil compaction. This process could be stronger in row than in ridge, covering with crop canopy. Compared to summer, autumn is relatively dry season, and harvesting could make soil structure loose.

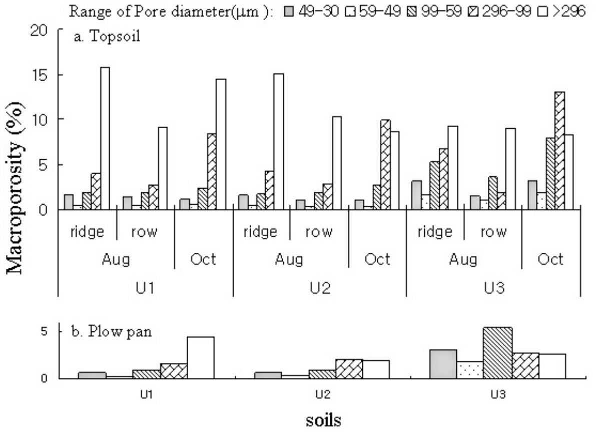

Fig. 5. Macropore size distribution as affected by different sampling times, layers, and positions, i.e., ridge or row of upland soils. Soil core samples of topsoil were sampled at 11 August, and 19 October, and those of plow pan at 19 October.

Relationship between *Df* and macroporosity Fragmentation fractal dimension of aggregate stability in wet-sieving and macroporosity showed in graphic form at fig. 6. The graph showed that the fractal dimension less than 3.1 had high correlation with macroporosity, especially more than 99 m. Besides, in the soils with the fractal dimension less than 3.1, the power function relation between saturated hydraulic conductivity and macroporosity more than 99 m had relatively high determinant coefficient, and vice versa. In other words, saturated hydraulic conductivity could be estimated from macroporosity in soils with water stable aggregate.

Higher D_f means lower water stability of aggregate. In other words, soils with D_f less than 3.1 are more aggregated than soils with D_f more than 3.1. Therefore, only aggregated soil had a relationship with

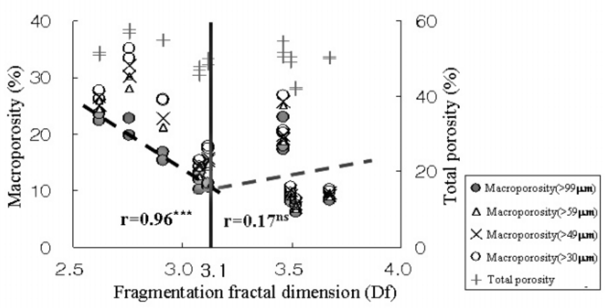

Fig. 6. The relationship between fragmentation fractal dimension (D_f) and macroporosity of upland soils.

macroporosity and successively could cause a macroporous flow. Actually, D_f has been used as indicator of fragmentation caused by different tillage operations or as a result of different cropping strategies (Crawford et al., 2000; Perfect et al., 1992; Perrier and Bird, 2003; Rasiah et al., 1995). This study suggested that Df might indicate the possibility of a macroporous flow.

The aggregate-based process models has a clear distinction between macropores and fine structured matrix. Inter-aggregate pores, macropores, act as the external world for the processes taking place in the soil matrix (White, 1985; Han et al., 2008). Preferential flow in macropores could be faster than in soil matrix. And the flow can include surface-applied nutrients or pesticides such as nitrate and atrazine, whereas solute in soil matrix can be protected from the flow (Young et al, 2001). On the contrary, if no distinction is possible between macropores and soil matrix, there is no boundary between the two types of media. Without such a boundary, the soil structure lacks an aggregate level at which aggregate models are meaningful. Particularly, there were many artificial disturbance such as tillage and compost application in arable soils, which could clear the boundary between macropores and soil matrix (Kay, 1989). Nevertheless, a newly generating structure after physical disturbance, could depend on water stable aggregate, which do not easily disintegrate against external forces such as rain drops (Six and Paustian, 2000). Figure 6 showed the possibility that aggregate stability in wet-sieving in upland arable soil may have strong correlation with macropores.

Conclusion

Fragmentation fractal dimension (D_f) would be relatively proper as the general characterization of the aggregate stability in wet-sieving rather than GMD and MWD, because D_f has no-dimensional process-based property. The relationship between D_f and macroporosity, especially more than 99 m, showed high correlation only in soils with D_f less than 3.1, which means more aggregated soils compared to soils with D_f more than 3.1. Besides, in the soils with the fractal dimension less than 3.1, the power function relation between saturated hydraulic conductivity and macroporosity more than 99 μm had relatively high determinant coefficient, and vice versa. Therefore, it could be thought that fragmentation fractal dimension is available for confirming macroporosity induced from aggregation.

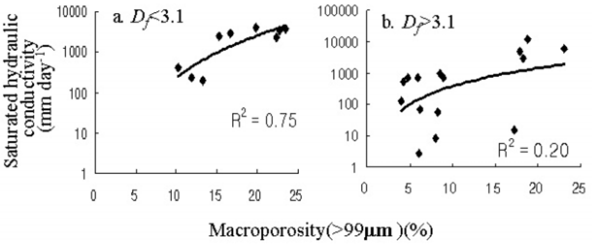

Fig. 7. The estimation of saturated hydraulic conductivity by macroporosity in different ranges of fragmentation fractal dimension (D_f) in upland soils.

References

Bronick, C.J. and R. Lal. 2005. Soil structure and management: a review. Geoderma 124: 3-22.

Crawford, J. M., Ya. A. Pachepsky, and W. J. Rawls. 2000. Integrating processes in soils using fractal models. In: Crawford, J. M., Ya. A. Pachepsky, and W. J. Rawls. Fractals in Soil Science. Developments in Soil Science 27. Elsevier.

Dalal, R. C., and B. J. Bridge. 1996. Aggregation and organic matter storage in sub-humid and semi-arid soils. In: Carter, M. R., and B. A. Stewart, Structure and Orgainc Matter Storage in Agricultural Soils. CRC Press, Boca Raton, FL, pp. 263-307.

Danielson, R. E. and P. L. Sutherland. 1986. Porosity. In: Klute, A. 1986. Method of soil analysis. Part 1. Physical and Mineralogical methods, 2nd edn. ASA and SSSA, Madison, WI.

Han, K. H., H. M. Ro, H. J. Cho, L.Y. Kim , S. W. Hwang, H. R. Cho, and K. C. Song. 2008. Mobility of nitrate and phosphate through small lysimeter with three physico-chemically different soils. Korean J. Soil Sci. Fert. 41:260-266.

Han, K. H.,H. J. Cho, H. S. Lee, D. S. Oh., and L.Y. Kim. 2007. Stable macro-aggregate in wet sieving and soil properties. Korean J. Soil Sci. Fert. 40:255-261.

Kay, B.D. 1989. Rates of change of soil structure different cropping system. Adv. Soil Sci. 12: 1-52.

Mandelbrot. 1993. The fractal geometry of nature. Freeman, New York.

Marshall, T. J. 1959. Relations between water and soil. Tech. Comm. 50, Commonwealth Bur. Soils, Harpenden, U.K.

McDonald, P. M. 1967. Disposition of soil moisture held in temporary storage in large pores. Soil Sci. 103(2):139-143.

McLaren, R .G. and K. C. Cameron. 1996. Soil Science. 2nd edition. Oxford University Press.

Mosley, M. P. 1979. Streamflow generation in a forested watershed, New Zealand. Water Resour. Res. 15(4):795-806.

NIAST. 2000. Method of soil and plant analysis. Published by National Institute of Agricultural Science & Technology. Suwon, Korea.

Oades, J. M. 1984. Soil organic matter and structural stability: mechanisms and implications for management. Plant Soil 76:319-337.

Perfect, E., V. Rasiah, and B. D. Kay. 1992. Fractal dimension of soil aggregate-size distributions calculated by number and mass. Soil Sci. Soc. Am. J. 56:1407-1409.

Perrier, E. M. A, and N. R. A. Bird. 2003. The PSF model of soil structure: A multiscale approach. In: Pachepsky, Ya. A., D. E. Radcliffe, H. M. Selim. Scaling Methods in Soil Physics. CRC Press LLC.

Rasiah, V., E. Perfect, and B. D. Kay. 1995. Linear and nonlinear estimates of fractal dimension for soil aggregate fragmentation. Soil Sci. Soc. Am. J. 59:83-87.

Six, J., E.T. Elliott, and K. Paustian. 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32:1350-1358.

Six, J., H. Bossuyt, S. Degryze, and K. Denef. 2004. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil & Tillage Research 79:7-31.

Sparks, D. L. 1996. Method of soil analysis. part 3. Chemical methods, 3rd edn. ASA and SSSA, Madison, WI.

Tisdall, J. M. and J. M. Oades. 1982. Organic matter and water-stable aggregates. J. Soil Sci. 62:141-163.

Turcotte, D. L. 1986. Fractals and fragmentation. J. Geophys. Res. 91:1921-1926.

White, R. E.. 1985. The influence of macropores on the transport of dissolved and suspended matter through soil. Adv. Soil Sci. 3:95-120.

Young, I. M., J. W. Crawford, and C. Rappoldt. 2001. New methods and models for characterizing structural heterogeneity of soil. Soil & Tillage Research 61:33-45.

파쇄프랙탈차원을 이용한 밭토양 내수성입단과 대공극률의 관계 평가

한경화 · 조현준 · 이협성 · 허승오* · 하상건

농촌진흥청 국립농업과학원

본 연구는 밭토양 내수성입단의 계절별 특성을 밝히고 파쇄프랙탈차원을 이용하여 대공극률과의 관계를 구명코자 수행하였다. 대상 토양은 토성이 다른 세 지점으로 고평통 (Fine, Typic Hapludalfs), 규암통 (Fine silty over coarse silty, Fluvaquentic Eutrudepts), 중동통(Coarse loamy, Typic Udifluvents)으로 경기도에 위치하였다. 봄, 여름, 가을에 불교란 시료를 채취하고 내수성입단과 대공극률, 토양이화학성을 측정하였다. 내수성입단은 파쇄프랙탈차원(D_f), 기하평균지름(GMD), 중량평균지름(MWD)의 세 가지로 계수화하였다. D_f는 MWD보다 GMD와 상관이 높게 나타났고, 무차원의 입단파쇄과정에 근거하여서 실험에 사용한 입단크기와 전처리과정의 영향을 덜 받아 내수성입단의 계수화에 적절하다고 판단할 수 있었다. 계절적으로 내수성입단은 여름〉봄〉가을 순으로 나타났고 생물활성과 토양수분의 영향으로 파악할 수 있었다. D_f 3.1이하의 토양에서 D_f와 대공극률과 역의 상관관계를 나타냈으며 특히 99 ㎛ 이상의 공극률과 상관이 높았으며 D_f 3.1이상의 토양에서는 상관이 나타나지 않았다. 또한 D_f 3.1이하의 토양에서는 대공극률과 포화수리전도도의 누승함수 적합도가 높게 나타났다. 따라서 내수성입단의 파쇄프랙탈차원은 입단화에 의한 대공극형성과 해석에 유용하다고 판단할 수 있었다.