Aggregate Stability: A Vital Component of the Health of Sandy Soils Used in Agriculture

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ABSTRAK

Kestabilan Kebersamaan: Komponen Utama untuk Kesehatan pada Lahan Berpasir untuk Pertanian. Kesehatan dan kualitas tanah merupakan komponen terpenting dalam pertanian yang berkelanjutan. Pemeliharaan kesehatan tanah berpasir sangat penting dilakukan, karena tekstur tanahnya ringan, memiliki kapasitas menahan air, dan menggunakan hara rendah serta mudah mengalami erosi. Stabilitas agregat diperkirakan merupakan indikator fisik kesehatan tanah berpasir, karena hal ini sangat berpengaruh terhadap sifat-sifat fisik (seperti ciri-ciri hidraulik, kekuatan tanah, dan erosi), sifat kimia (seperti daur hara), dan biologi (seperti aktivitas mikroba). Liat dan bahan organik memegang peranan penting dalam agregasi dan stabilitas tanah. Salah satu strategi untuk meningkatkan stabilitas agregat tanah berpasir adalah penambahan liat dan bahan organik. Hal ini diharapkan dapat meningkatkan aktivitas mikroba tanah dan memberikan kondisi yang lebih baik untuk pertumbuhan akar.

Kata kunci: Kesehatan tanah, stabilitas agregat, tanah berpasir, produksi tanaman.

ABSTRACT

Aggregate Stability: A Vital Component of the Health of Sandy Soils Used in Agriculture. The health or quality of soil is considered to be the most important component in a sustainable agriculture. Maintaining health of agriculture sandy soil is urgently needed because the soils are light in texture, have low capacities to retain water and applied nutrients, and prone to erosion. Aggregate stability is probably the most important physical indicator of the health of sandy soil, because it has a major influence on the soil physical (e.g. hydraulic characteristics, soil strength, and erosion), chemical (e.g. nutrient cycling), and biological (e.g. microbial activity) properties. Clay and organic matter play important roles in the soil aggregation and stability. One strategy to increase aggregate stability of the sandy soil is by addition of clay and organic matter. Incorporation of clay and organic matter is expected to increase the aggregate stability of sandy soils, which is in turn will increase the soil microbial activity and provide more suitable conditions for root growth.

Key words: Soil health, aggregate stability, sandy soil, crop production.

INTRODUCTION

Traditionally agricultural soil management practices have focused on plant productivity. However, soil degradation is a serious problem in many regions of the world as is indicated by declines in various soil health indicators (Arshad and Martin 2002, Wienhold *et al*. 2004). For example, intensive tillage can decrease aggregate stability (Pagliai *et al*. 2004), increase soil erosion (Basic *et al*. 2004), increase gas emission (Lal 2004) and decrease soil organic matter content (Diekow *et al*. 2005, Sainju *et al*. 2005). Soil degradation may decrease productivity and lead to issues of environment health such as global warming (Rees *et al*. 2005, Schulze and Freibauer 2005) and the occurrence of residual chemicals in the subsoil and ground water (Prunty and Greenland 1997).

There is an urgent need to widely implement more sustainable soil management practices in agriculture to improve and maintain soil quality (Carter 2002), but it has been claimed that soil management strategies that only focus on environmental issues might endanger productivity of food and fibre (Wander *et al*. 2002). This claim relates to increases in monoculture production of grains, cultivation, and dependence on chemical fertilizers and pesticides to increase crop yields. On the other hand, these intensified production practices often cause soil degradation as indicated by increasing erosion and ground water contamination (Matson *et al.* 1997), which may have an influence on decreasing crop production. Therefore, the concept of sustainable soil management practices needs to be based on an understanding among ecologists, socio-economists, environmentalists and land managers to ensure that a balance is developed that includes consideration of the impacts of soil management practices on productivity, the environment, economic returns and societal issues (Wander *et al.* 2002). There is a challenge to develop soil management practices that balance the requirements for production and environmental health (Doran and Safley 1997).

Soil health has been defined as 'the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal and human health' (Doran and Safley 1997). It is very important to maintain the sustainability of agriculture by establishing ongoing assessment of the condition and health of the soil (Doran and Safley 1997, Arshad and Martin 2002). The health or quality of soil is considered to be the most important element of sustainable agriculture (Acton and Gregorich 1995, Warkentin 1995) and it depends on a balance among physical, chemical and biological components of soil fertility (Abbott and Murphy 2003).

Soil structure is an important factor that influences the capacity of soil to support agricultural production, soil carbon sequestration and water quality (Bronick and Lal 2005). An important measure of soil structure is aggregate stability (Six *et al*. 2000). Soil aggregation is the result of soil particle arrangement, flocculation and cementation being influenced by soil properties, biota and environmental process, such as clay and organic matter content and types, microbial biomass, and hyphal length. Aggregate stability is mediated by soil organic carbon, soil organisms, ionic bridging, clay and carbonates (Bronick and Lal 2005). Aggregate stability may be the most important physical indicator of the health of sandy soil because it has a major influence on soil physical (e.g. hydraulic characteristics, soil strength, and erosion), chemical (e.g. nutrient cycling), and biological (e.g. microbial activity) properties. Sandy soils are light in texture, have a low capacity to retain water and applied nutrients, and are prone to erosion. They also have less capacity to form aggregates than do soils with lower of sand contents. For sandy soils, increased aggregate stability may improve biological and chemical aspects of soil fertility, enhancing porosity and minimizing erodibility (Bronick and Lal 2005).

The dynamics of factors associated with soil health have been extensively reviewed (Guérif *et al*. 2001, Kay and Van den Bygaart 2002, Mrabet 2002, Sauerbeck 2001, Zentner 2002). However, these reviews focus mainly on the effect of soil tillage on soil physical and chemical properties. While there is considerable evidence about the effect of tillage on soil properties for a broad range of soil types, there is less information about their effects on soil biological properties associated with soil physical properties. Soil biological properties are highly sensitive to land management practices (Pankhust *et al*. 1997), but there is relatively little information about the effect of management practices on biological aspects of the health of sandy soil.

This review focuses on the effect of soil management practices on the state of sandy soil, especially the effects of clay, organic matter, temperature, particle size distribution and plant roots. First, an overview is given of the general properties that might indicate the health of sandy soils used for agricultural production. This is followed by an evaluation of the effects of land management practices on sandy soil, including interactive processes associated with the soil physical and biological environment.

PROPERTIES OF SANDY SOIL

Sandy soils characteristically consist of loose soil particles because the cohesion between them is weak (Shepherd *et al*. 2002). This natural property of sandy soil can cause problems in their use for agricultural production. For example, in the Western Australia wheat belt, soils are often uniform in texture and contain more than 85% sand (Farrington and Campbell 1970). They are also inherently low in all aspects of soil fertility and have a low capacity to retain water and applied nutrients (Farrington and Campbell 1970). In contrast, soils dominated by clay form fine granular aggregates because the clay particles are electrically charged and the oppositely charged surfaces provide the basis of a greater aggregation (Shepherd *et al*. 2002). For a range of soil analyses, the properties of sandy soils (especially soil biomass C) are generally lower than those of clay soils.

Deleterious impacts of management practices on sandy agricultural soils have been reported. For example, cultivation of sandy soils more than once and up to three times prior to sowing, increased run off and decreased organic C and aggregate stability (Packer *et al*. 1992). It might be important to establish guidelines for soil management practices for agricultural sandy soils with the objective of reducing erosion, preserving organic matter and optimizing water use. Agricultural management that takes into account soil biological processes has the potential to increase the sustainable use of sandy soils in agriculture, because soil organism activity plays many important roles in soils, such as release of nutrients, improving soil structure, and the breakdown of organic contaminants (Jenkinson and Ladd 1981).

Aggregate Stability as a Vital Component of the Health of Sandy Soils Used for Agriculture

Soil aggregation is defined as the clustering or grouping of soil particles in which the forces holding the particles together are much stronger than the forces between adjacent aggregates (Martin *et al*. 1955). Generally, the force holding the particles together is expressed as soil aggregate stability and assessed by determining the resistance of the aggregates to dry-sieving or wet sieving.

There are several methods for quantifying soil aggregate size distribution and aggregate stability (Kemper and Rosenau 1986, Elliot 1986, Cambardella and Elliot 1993). The suitability of these methods depends on the purpose of the study. The most common approaches are based on the wet-sieving methods (Kemper and Rosenau 1986) whereby a sequence of submerging and sieving in water imitates the natural stresses involved in the entry of water into the soil aggregates (Marquez *et al*. 2004). However, the initial water content of the soil aggregate before wet sieving controls the severity of disruption (Kemper and Rosenau 1986). Another method used to determine aggregate stability is capillary-wetted and slaked pretreatments (Elliott 1986, Cambardella and Elliot 1993). In this method, the soil aggregate involves slow wetting before sieving involves capillary-wetted pretreatment. Consequently, this pretreatment causes minimal disruption, because slowly moistened aggregates do not increase the air pressure in the pores as the air escapes with minimal aggregate disruption (Märquez *et al*. 2004). In contrast, the slaked pretreatment produces substantial disruption, because the air that is trapped inside the soil pores is rapidly compressed by water entry when air-dry soil is submerged in water. But, the slaked pretreatment method might not be suitable for determining the aggregate stability of sandy soil where air entrapment may not be a problem.

Soil aggregation and its stability are dynamic process, because both are affected by many factors, such as soil management practices, soil properties and the soil environment (such as soil temperature and moisture content) (Tisdall and Oades 1982, Bronick and Lal 2005). Aggregate stability is a vital property of soils used for agriculture because it is often related to soil fertility and agronomic productivity (Bronick and Lal 2005). Therefore, it is important to identify factors that influence soil aggregation and its stability.

Factors affecting aggregate stability

Soil aggregate stability is the result of complex interactions among soil biological, chemical and physical processes (Tisdall and Oades 1982). Three groups of factors affecting aggregate stability are abiotic (clay, sesquioxides, exchangeable cations, and particle size distribution), biotic factors (soil organic matter, micro-organisms, plant roots, and soil fauna), and environmental factors (temperature and moisture) (Bronick and Lal 2005). In sandy soils, the distribution of particle sizes might also contribute to the stability of aggregates. For

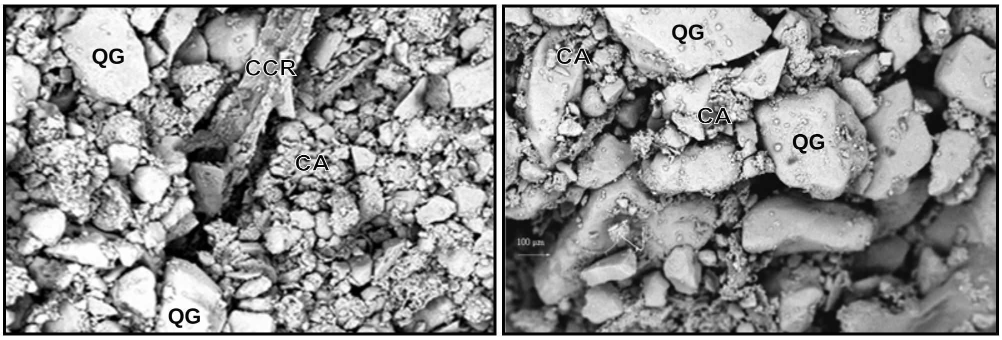

Figure 1. An aggregate of <250 µm soil (top) and an aggregate of whole soil (bottom) observed with Variable Pressure Scanning Electron Microscope Zeiss 1555. The top soil is denser than the bottom soil and it has a higher macroaggregate stability (45%) than the whole soil (15%). Aggregate samples >4 mm were prepared by incubating sandy soils composed of the two different size fractions from a soil collected at Meckering, Western Australia. Macroaggregate stability was determined by wet sieving. QG = quartz grains, CA = clay aggregate; CCR = clay coated aggregate.

example, aggregates of sandy soil containing smaller size fractions (<250 μm diam.) were more stable than were aggregates in whole sandy soils containing a wide range of soil fractions (Figure 1). Soil aggregates composed of smaller size fractions appear more compact and are denser than aggregates composed of larger size fractions. Closer packing of aggregates with smaller size particles may cause strong cohesion between soil particles which result in more stable aggregates.

Different models of the formation and stabilization of aggregates involve different contributions of inorganic and organic materials. Soil aggregation can be mainly due to the cementing of soil particles by mineral substances (Miller and Jastrow 1992). In the presence of plants and in soils where organic matter is the major binding agent, the arrangement of microaggregates (<0.25 mm diam.) into macroaggregates (>0.25 mm diam.) can be facilitated by hyphae of arbuscular mycorrhizal fungi and saprophytic fungi in association with fibrous roots (Tisdall and Oades 1982, Miller and Jastrow 1990). Hyphae of arbuscular mycorrhizal fungi bind soil particles into water stable aggregates (Tisdall and Oades 1979). Furthermore, mucigels and polysaccharides released by microorganisms and roots are involved in binding soil particles and stabilizing aggregates (Oades 1984). The role of hyphae of arbuscular mycorrhizal fungi in aggregation of sandy soils has been investigated by Degens *et al.* (1996), but the specific role of organic compounds was not identified. It has been reported that glomalin, an insoluble glycoprotein produced by arbuscular mycorrhizal fungi, is associated with stabilization of soil aggregates (Wright and Upadhyaya 1998, Franzluebbers *et al*. 2000). From 37 soil samples representing a variety of geographic regions and crop histories, it was found that aggregate stability was linearly related ($p<0.001$) to glomalin content (mg/g of aggregates) of these soils (Wright and Upadhyaya 1998). However, the mechanisms of the relationship between glomalin and aggregate water stability are not well defined yet (Rillig 2004). Previously, it was thought that glomalin is secreted into the soil and acts as a soil binding agent (Wright and Upadhyaya 1998). It is likely that the secretion and binding mechanisms are not the case since glomalin is contained in the hyphal/sopre walls (Rillig 2004). In addition, the positive relationship between glomalin and water stable aggregate was mostly occur in soil with high organic matter content, so that glomalin contributes to aggregate stability because the compounds block soil pores which in turn reduce penetration of water into aggregates. Glomalin may be as a part of soil protein which partly produced by arbuscular mycorrhiza fungi, so that the term of glomalin-related soil fractions (GSRP) is proposed by Rillig (2004).

Aggregate stability in sandy soils may be the most important aspect of soil health in assessing susceptibility of soil to wind erosion. For sandy soils, Degens *et al.* (1996) suggested that hyphal cross-linkages between sand grains may be a dominant mechanism for maintaining the stability of aggregates. Soil amendment with glucose did not affect water stable aggregates of sandy soil (Degens and Sparling 1996). In this study, ^{14}C microbial biomass and ^{14}C microbial products were poorly related to amounts of water stable aggregates, and there was no relationship between clay content and microbial biomass C or microbial biomass products of different aggregate size of sandy soil (Degens and Sparling 1996). In contrast, Kiem and Kandeler (1997) found that microbial biomass had a considerable influence on increasing the aggregate stability of sandy soils. These different conclusions are likely to be due to differences in the mechanisms of aggregate stability in the soils studied. In sandy soils used by Degens and Sparling (1996), aggregation was mainly due to the pattern of fungal hyphal growth through the soil (Degens *et al.* 1994). For the sandy soils investigated by Kiem and Kandeler (1997), aggregate stabilization was primarily associated with the microbial products acting as soil binding agents rather than the increased size of microbial biomass. Furthermore, Léon-Gonzáles *et al*. (2000) reported that the addition of organic material in the form of compost (prepared from urban market waste content of composition 10.6 g/kg N, 3.9 g/kg P, 11.1 g/kg K, 19 g/kg Ca, 6 g/kg Mg) significantly increased the formation of macroaggregates (>1mm) in sandy soils that were stable to wind erosion in Tulyehualco, Mexico. However, the water stability of macroaggregates >1 mm was less than for treatments without added with compost. It was thought that low content of clay in the soil (7% clay) caused the low water stability of the macroaggregates (Léon-Gonzáles *et al*. 2000).

In sandy soil exposed to different management practices, several factors may be involved in aggregate stability and they may have synergistic effects. The inter-relationship of some factors is expected to occur because soil management practices alter physical, chemical and biological soil properties (Wang and Gong 1998, Schipper and Sparling 2000, Chan *et al*. 2001). For example, differences in aggregate stability in a tropical Ultisol (Sabah, Malaysian Borneo) were related to the amount of organic C, clay content and exchangeable sodium percentage (ESP) at sites undergoing erosion (Chappell *et al.* 1999, Franzluebbers and Arshad 1996). In a tropical Ultisol (Sabah, Malaysian Borneo), organic C was the most important governing factor, accounting for 56% of the variance in aggregate stability (Chappell *et al.* 1999). Another demonstration of the inter-relationships among soil characteristics is shown by a long-term continuous cultivation study of Western Australian sandy soils which was associated with decreased soil pH and increased hard-setting (Gazey and O'Connell 2001). Acidic soils in this area have been treated with lime with or without reduced tillage. The experiments have focussed on the effect of treatments on plant growth and yield (Gazey and O'Connell 2001), with little information gained about changes in soil biological properties. Several other studies have reported that addition of lime increased microbial activity (Stenberg *et al*. 2000) and aggregate stability (Chan and Heenan 1999). The degree of disturbance of the soil associated with tillage affects soil water movement, soil organic matter, and microbial activity (Stenberg *et al*. 2000), which in turn will affect the binding of soil particles.

In sandy soils, aggregate stability may also be sensitive to soil management practices (including intensive tillage) because the binding of sand grains is largely mediated by biological factors (Degens 1997). Consequently, identifying biological changes under different soil management practices could be used to identify possible forms of manipulation of soil and/or plant rotations that may enhance soil aggregate stability. The soil management practices that may be applied to sandy agricultural soils to sustain their capacity to support plant growth include the addition of clay and organic matter as these properties have been identified in this review as having a major influence on the soil structure of sandy soils.

Additions of clay and organic matter may change soil physical properties (such as soil aggregation, soil strength, and particle size distribution) through cementation, cohesion and replacement of soil particles. Clay and organic matter have roles as cementing agents and are involved in soil aggregate stability (Tisdall and Oades 1982), so that addition of these potential cementing agents may increase aggregate stability. The cementing action of clay is due it forming bridges between soil particles which increases soil strength, but addition of organic matter may cause the bridges to become fragile (Harper and Gilkes 1994). Addition of clay may also change the soil particle distribution within a particular layer of soil by replacing coarse soil particles. Increasing aggregate stability will change soil chemical properties through the production, protection or distribution of organic matter and CO_2.

An increase in soil organic matter and CO_2 may occur because macroaggregates are formed from microaggregates and organic materials (Tisdall and Oades 1982), and added organic matter and more labile organic matter are more concentrated in macroaggregates than in microaggregates (Elliot 1986). As a source of energy, increasing soil organic matter will increase microbial biomass and microbial activity which will in turn produce more microbial-derived binding agents. Finally, increases in microbial-derived binding agents and hyphal length will increase aggregate stability through binding and enmeshment mechanisms.

The involvement clay in aggregate stability

Aggregate stability depends on the internal cohesiveness between constituent particles, particularly clay particles (Andreu *et al*. 2001), because aggregates are composed by individual soil particles. Clay is involved in the arrangement of microaggregates, and these microaggregates are grouped together by organic matter to form macroaggregates (Tisdall and Oades 1982). Consequently, the arrangement of soil particles to form aggregates is influenced by soil texture (Shepherd *et al*. 2002). Soils dominated by clay may form fine granular aggregates due to the clay particles being electrically charged and the conjunction of oppositely charged surfaces providing the basis of a greater aggregation (Shepherd *et al*. 2002). While clay is one of the cementing agents that binds soil particles together to form soil clusters, it also has the potential to protect soil organic matter from decomposition (Hassink *et al.* 1993, Bronick and Lal 2005) by limiting its accessibility or creating unsuitable conditions for microbial activity (Strong *et al.* 1998).

The involvement of clay in soil aggregation and stabilization is associated with control of the expansive properties of soil (Oades 1993). The expansion of soil involves physical forces of shrinking and swelling due to changes in the water status, freezing and thawing, tillage or movement of soil biota (Oades 1993). It has generally been reported that the aggregate stability of soils with various textures is related to clay content (Kemper *et al.* 1987, Attou *et al*. 1998); soil with more clay should have more aggregates and more stable aggregates than soil with less clay. However, the effectiveness of clay in soil aggregation is determined by the dispersibility of the clay (Kay 1990). Furthermore, the dispersibility of clay is determined by soil properties including soil particle size and the presence of dispersing agents (such as organic anions) or cementing agents (such as organic matter, Ca carbonates, Mg carbonates, and oxides of Si, Fe, and Al). By comparing two soils which had different degrees of dispersion, Nelson *et al.* (1999) found that the content and the types of soil organic matter was a more dominant factor in controlling the degree of dispersion than the type of clay. The two soils contained illite and kaolin clay, but the easily dispersed clay had lower organic C content than the difficult to disperse clay. In addition, the easily dispersed clay contained a high proportion of amino acids (which had a role as a dispersing agent). In contrast, the difficult to disperse clay had a high proportion of aliphatic materials in the top soil and carbohydrate in the subsoil indicating that these materials acted as cementing agents (Nelson *et al.* 1999). Consequently, it is expected that the aggregate stability of a sandy soil could be enhanced by an interaction between clay and organic matter content.

The process of soil aggregation and stabilization also depends on clay type (Caravaca *et al.* 2001). Soils dominated by clay minerals with a high specific surface area have a high capacity for absorbing humic substances and consequently for stabilizing aggregates (Parfitt *et al*. 1997). The absorption of organic matter in the form of humin was higher in a beidellitic clay soil than in a illitic clay soil (Caravaca *et al*. 2001). The aggregate stability of beidellitic clay soil was significantly related to organic matter and humin content of the fine silt fraction (Caravaca *et al*. 2001).

There is strong evidence that clay can be used to ameliorate water repellent sandy soil and application of clay is becoming a more common amelioration practice in south-western Australia (Carter *et al*. 1997). The addition of clay to water repellent soil may also increase the stability of aggregates. In another study it was known that the aggregate stability of microaggregates was positively related to clay content, but the stability of macroaggregates (>2mm) depended on the organic matter content when the organic matter content was greater than 5 to 6% (Boix-Fayos *et al.* 2001). Furthermore, Amato and Ladd (1992) found a strong relationship between clay content and microbial biomass derived from ^{14}C-glucose.

An increase in kaolin clay content by 1-2% can play an important role in the prevention of water repellency in very sandy soils, and increasing the proportion of clay in the soil may increase the strength of sandy soil (Harper and Gilkes 1994). In Western Australia, the Western Australia Non-Tillage Farmer Association (WANTFA) established an experiment to identify the effect of subsoil clay dominated by kaolin on water repellent sandy soil with a focus on the effect of clay on crop yield. Effects of clay addition on soil properties such as soil aggregate stability and protection of soil organic matter from degradation at the site have not been investigated. Identifying the effect of added clay on the aggregate stability of water repellent sandy soil and possible mechanisms involved is desirable due now that the common practice of reducing water repellency by addition of clay is used in the field.

The involvement of organic matter in aggregate stability

The involvement of soil organic matter in soil aggregate stability is through the physico-chemical interactions of organic compounds with clay and fine silt particles (Caravaca *et al*. 2001). Hence, studies of the impact of soil degradation processes on soil properties associated with soil management have mainly focused on changes in soil physical characteristics and loss of organic matter (Franzluebbers and Arshad 1996, Chappell *et al*. 1999). However, in sandy soils which do not have physico-chemical properties required for soil stabilization, soil biological properties could have an important role in aggregate stability (Oades 1993). The total organic C content of soil is considered a poor indicator of the amounts of organic materials involved in stabilizing macroaggregates and macroaggregate stability is sensitive to short-term management (Tisdall and Oades 1982). Consequently, recent studies have concentrated on identifying and understanding labile organic C fractions involved in the short-term (<2 years) stabilization of aggregates, and have generally focused on the role of microbial biomass C as an indicator of the labile organic C fractions involved in stabilizing macroaggregates (Degens and Sparling 1996, Kiem and Kandeler1997, Boix-Fayos *et al.* 2001).

The soil microbial biomass has been defined as living organisms smaller than 10 µm (Schloter *et al*. 2003). Microbial biomass measurements are often claimed to be useful as a soil biological indicator of soil microbial population because of their relatively simple determination in a range of soils (Webster *et al.* 2001). Soil microbial biomass content has been considered as an integrative indicator of the microbial component of soil because it is one of the few fractions of soil organic matter that is biologically meaningful and also sensitive to soil management (Powlson 1994). Several studies have shown that soil microbial biomass C has a positive relationship with the degree of soil aggregation (Kiem and Kandeler 1997). The microbial biomass has a positive effect on soil aggregation but this is not because the biomass is directly involved in stabilizing aggregates as it seems likely that the biomass indicates previous microbial turnover of organic C and the production of bonding compounds and binding structures (Degens 1997). Hence, soil microbial activity and microbial diversity through their involvement in C turnover and in the production of bonding compounds may have significant roles in providing aggregate stability of soil under various soil management practices. However, there is still insufficient information about changes in microbial activity and diversity due to changes in soil management practices (such as the addition of clay and organic matter to sandy soils) in relation to aggregate stability, which could be applied to sandy soils.

Implication of Improvement of the Health of Sandy Soils

For sandy soils, manipulative techniques to increase aggregate stability include creating a suitable environment for hyphae and roots to grow. Manipulative techniques for sandy soils (which generally have low contents of water and nutrients for plant growth and are prone to erosion) could include applying clay and organic matter as soil amendments. Improved soil physical properties result in greater root distribution and penetration and hence greater nutrient and water uptake (Dexter 1988). In a study of soil with different textures, Emerson (1995) found that water retention by loam and fine sandy loam increased linearly with clay and organic C content. In addition, Bruand and Tessier (2000) indicated that water retention by a clayey soil varied according to the amount of clay and the size of the elementary particles. Furthermore, Barzergar *et al*. (2002) demonstrated that addition of organic materials increased soil water retention at suctions less than -100 KPa, infiltration rate, aggregate stability and wheat grain yield for a fine loam soil.

While additions of clay and organic matter to sandy soils may change soil biological and physical properties, changes may also occur in term of relationships between soil properties. For clay and loam soils, several authors have reported that the length of hyphae and plant roots contributed significantly to soil aggregation (Bearden and Peterson 2000, Boix-Fayos *et al*. 2001). Hyphal and root enmeshment of soil particles into soil clusters has been suggested to be the main mechanism by which aggregates are stabilised in some soils (Miller and Jastrow 1992). Gale and Cambardella (2000) reported on the role of fungi and plant roots in increasing the retention of particulate organic matter (labile organic C) in a no-till soil. Furthermore, there is considerable evidence indicating that labile carbohydrate C fractions are important in stabilising macroaggregates in clay and loam soils (Cambardella and Elliot 1993). Thus, plants that have a root architecture dominated by many fine roots and roots hairs may have a greater capacity to release organic C throughout the soil and exert a greater influence on aggregation than plants with coarse roots systems (Degens 1997). As different plants have different root morphologies and associations with mycorrhizal fungi, they will have different effects on binding of soil particles (Oades 1993). The hyphae of arbuscular mycorrhizal fungi produce glomalin that may have an important role in binding soil particles and strains of these fungi differ in their hyphal distribution (Abbott and Robson 1985, Rillig 2004). Combinations of arbuscular mycorrhizal fungi with dense hyphae and host plants with dense root architecture may have a synergistic effect on the cohesiveness of particles in sandy soils in relation to microbial biomass C.

CONCLUSIONS

Sandy soils are light in texture and prone to erosion, so that increasing the aggregate stability of sandy soil is important for improving its fertility, increasing its productivity, and minimizing erodibility. Clay and organic matter have an important role in soil aggregation and stability. Incorporation of clay and organic matter is expected to increase the aggregate stability of sandy soils which in turn will increase soil microbial activity and provide more suitable condition for root growth. Also, addition of clay and organic matter will interact with other soil particles to form aggregates.

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