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Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review

R.J. Haynes^{1,*} & R. Naidu²

¹*New Zealand Institute of Crop & Food Research, Canterbury Agriculture and Science Centre, Private Bag 4704, Christchurch, New Zealand;* ²*CSIRO Division of Soils and the Cooperative Research Centre for Soil and Land Management, Private Bag No.2, Glen Osmond, South Australia, 5064, Australia;* **Present address: Department of Agronomy, University of Natal, Private Bag X01, Scottsville, Pietermaritzburg, 3209, Republic of South Africa, fax: 3312505426. e-mail: haynesd@agron.unp.ac.za*

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Abstract

The effects of lime, fertilizer and manure applications on soil organic matter status and soil physical properties are of importance to agricultural sustainability. Their effects are complex and many interactions can occur. In the short-term, liming can result in dispersion of clay colloids and formation of surface crusts. As pH is increased the surface negative charge on clay colloids increases and repulsive forces between particles dominate. However, at higher lime rates, Ca²⁺ concentrations and ionic strength in soil solution increase causing compression of the electrical double layer and renewed flocculation. When present in sufficient quantities, both lime and hydroxy-Al polymers formed by precipitation of exchangeable Al, can act as cementing agents bonding soil particles together and improving soil structure. Liming often causes a temporary flush of soil microbial activity but the effect of this on soil aggregation is unclear. It is suggested that, in the long-term, liming will increase crop yields, organic matter returns, soil organic matter content and thus soil aggregation. There is a need to study these relationships on existing long-term liming trials.

Fertilizers are applied to soils in order to maintain or improve crop yields. In the long-term, increased crop yields and organic matter returns with regular fertilizer applications result in a higher soil organic matter content and biological activity being attained than where no fertilizers are applied. As a result, long-term fertilizer applications have been reported, in a number of cases, to cause increases in water stable aggregation, porosity, infiltration capacity and hydraulic conductivity and decreases in bulk density. Fertilizer additions can also have physico-chemical effects which influence soil aggregation. Phosphatic fertilizers and phosphoric acid can favour aggregation by the formation of Al or Ca phosphate binding agents whilst where fertilizer NH₄⁺ accumulates in the soil at high concentrations, dispersion of clay colloids can be favoured.

Additions of organic manures result in increased soil organic matter content. Many reports have shown that this results in increased water holding capacity, porosity, infiltration capacity, hydraulic conductivity and water stable aggregation and decreased bulk density and surface crusting. Problems associated with large applications of manure include dispersion caused by accumulated K⁺, Na⁺ and NH₄⁺ in the soil and production of water-repellant substances by decomposer fungi.

Introduction

Lime and fertilizers are common amendments that are routinely applied to agricultural soils. Their effects on soil fertility and plant nutrition are well known but

their application may well have beneficial effects on other soil properties such as soil physical conditions. Indeed, liming is believed by many farmers to improve soil structure although the mechanism by which this occurs is somewhat unclear (Davies and Payne, 1988).

Certainly, the application of organic manures, which are generally added as a nutrient source, often improves soil physical conditions particularly in arable soils (Davies and Payne, 1988; Khaleel et al., 1981).

Maintenance of optimum soil physical conditions is an important component of soil fertility management. Breakdown of soil aggregates, and the attendant poor soil structural condition, often restricts crop root growth and thus the efficient exploration of the soil profile for water and nutrients (Gregory, 1988). It may also result in ponding of water at the soil surface and increased prevalence of root diseases or, following drying, formation of a surface cap which restricts germination and seedling emergence.

Lime and fertilizer applications could influence aggregate stability (the ability of soil aggregates to withstand the degrading action of water) and hence other related soil physical properties by at least two contrasting mechanisms. Firstly, by increasing crop yields, they could increase organic matter returns to the soil (as crop residues) and thus raise soil organic matter content. Various forms of organic matter (e.g. humic molecules and polysaccharides) are intimately involved in binding soil aggregates together and aggregate stability is often closely correlated with soil organic matter content (Haynes and Beare, 1995). Secondly, addition of lime and fertilizers to soil will influence the chemical composition of soil solution. The pH, ionic strength and ionic composition of soil solution can greatly influence dispersion / flocculation of clay particles and thus soil aggregation.

In this paper, the effects of applications of (i) lime, (ii) fertilizers and (iii) manures on soil physical conditions are reviewed. Their effects are complex and many interactions are possible. For simplicity, effects are considered to be (i) direct through their influence on physico-chemical processes (i.e. dispersion / flocculation) or (ii) indirect through their influence on soil organic matter content and soil biological activity. Surprisingly little data is available regarding the effects of lime and fertilizer applications on these properties and processes and where experimental results are sparse, the most likely mechanisms are proposed and discussed using data from field and laboratory studies in related areas. Topics where there is a need for further research are highlighted. The role of gypsum as an ameliorant for sodic soils has been discussed elsewhere (Naidu et al., 1993; Shainberg et al., 1989) and is beyond the scope of this review.

Lime additions

In temperate regions, the conventional aim of liming is to raise soil $\text{pH}_{(\text{water})}$ into the range of 5.7 - 6.5, often with a target pH of about 6.0. This is considered to provide optimum conditions for growth of many temperate crop species. By contrast, many reports dealing with liming in tropical regions emphasize the hazard of overliming that accompanies attempts to adapt temperate region liming practices to the tropics (Pearson, 1975). In tropical regions, large increases in crop yields can be achieved with minimal applications of lime due to alleviation of Al toxicity and/or Ca deficiency. On highly-weathered acid soils of the tropics, lime rates are normally based on neutralization of exchangeable Al and often result in soil $\text{pH}_{(\text{water})}$ values in the range of 5.3 - 5.6 (Kamprath, 1984; Pearson, 1975). The reasons for lime-induced crop yield depressions are many-fold and include deficiencies of K, Mg, Si, P, Zn and Cu (Haynes, 1984). Fortunately, the cost and availability of lime in most areas of the tropics automatically prevents use of more than minimal rates and overliming is extremely uncommon.

In both temperate and tropical regions reports regarding the effects of liming on the physical properties of soils are conflicting. Liming has been reported to increase clay dispersion and reduce aggregate stability and infiltration rates significantly (Castro and Logan, 1991; Ghani et al., 1955; Kamprath, 1971; Roth and Pavan, 1991; Tama and El-Swaify, 1978). However, other workers have observed that liming decreases surface cracking (Hoyt, 1981) and increases water holding capacity (Hoyt, 1981; Kohn, 1975), aggregate stability (Czeratzki, 1972) and infiltration (Castro and Logan, 1991; Roth et al., 1986).

These contrasting results can be explained principally in the terms of (1) the short-term effects of liming on dispersion of soil colloids, (2) the flocculating and cementing actions of CaCO_3 and precipitated hydroxy - Al polymers, and (3) the longer-term effects of liming in stimulating crop growth, C returns to the soil and soil biological activity.

1. Dispersion caused by increasing pH

Dispersion/flocculation phenomena are important factors determining the effects of liming on soil physical properties (Sumner, 1992). Cations near the negatively-charged clay surfaces are subject to an electrostatic attraction toward the surface as well as a tendency to diffuse into bulk solution. As a result, the

concentration of cations diminishes exponentially as a function of distance from the clay surfaces. The partition of cations between surface sorption in the diffuse layer and solution is termed the electrical double layer. The formation of the double layer leads to mutual repulsion of opposing clay surfaces in dilute electrolyte solutions. As the valency of the cation and/or the solution ionic strength increases, the diffuse layer is compressed and the repulsive force decreases.

Attractive forces also exist between clay particles and these are often dominated by Van der Waals forces. These attractive forces diminish rapidly with increasing separation distance. Thus, as the double layer is compressed attractive forces become more important. Where the net force is attractive, the clay particles remain close together and are described as flocculated. Conversely, if the net force is repulsive the particles move further apart and may exist as separate entities in a dispersed state.

At low pH, acid soils are normally flocculated. High Al^{3+} and H^+ activity in soil solution promotes compression of the double layer and flocculation of clays (Roth, 1992). Attraction between positively charged Al and Fe hydrous oxides and negatively charged clay surfaces and bridging between organic matter and clay surfaces also promote flocculation. As pH is raised by liming the net negative charge on soil surfaces is increased and the ratio of negative to positive charges also increases. At the same time Al^{3+} activity declines as Al precipitates as hydroxy-Al polymers. As a result, repulsive forces between particles dominate and lead to dispersion. Tama and El-Swaify (1978), for example, reported that liming a Hawaiian soil from $\text{pH}_{(\text{water})}$ 4.5 up to 6.0 resulted in increased dispersion of soil aggregates. Dispersed clay colloids result in undesirable soil physical properties, such as surface crust formation, pore clogging and slow water penetration. Results presented in Figure 1 demonstrate that for a Brazilian Oxisol, liming up to about $\text{pH}_{(\text{KCl})}$ 6.5 and incubation for six weeks resulted in increased clay dispersion and reduced infiltration rates. An increase in water dispersible clay following liming has also been observed by other workers when acidic tropical soils ($<\text{pH}_{(\text{water})}$ 4.0) are limed into the range of 5.0 to 6.0 (Castro and Logan, 1991; Roth et al., 1986).

In most field experiments, these detrimental effects of liming on soil structure have been measured in the first 1-3 months following lime applications (Roth, 1992). After a period of 6 months, liming normally results in improved soil aggregation and increased aggregate stability and infiltration capacity. The rea-

sons for this improvement in soil structure are discussed below.

2. Flocculating and cementing agents

Direct positive effects of liming on soil structure can be ascribed to the flocculating and cementing actions of CaCO_3 itself and of newly precipitated Fe and Al oxides and hydroxides. As shown in Figure 1, even in short-term studies very high lime rates (i.e. $>\text{pH}_{(\text{KCl})}$ 6.0) can result in renewed flocculation of clays and an increase in infiltration. The high Ca^{2+} concentrations and high ionic strength can result in compression of the double layer thereby decreasing the repulsive force between soil particles. Greene et al. (1978), for example, found that rapid coagulation occurred immediately following mixing of illite and saturated $\text{Ca}(\text{OH})_2$ solutions. Scanning electron microscopy showed that the Ca-illite particles formed flocs in which the individual crystals were randomly oriented with respect to each other. Flocculation of the extracted clay fraction of soils (Rimmer and Greenland, 1976) and intact soils (Roth and Pavan, 1991) in the presence of high Ca^{2+} concentrations has also been observed. In sodic soils where high concentrations of exchangeable and solution Na^+ favour dispersion, the addition of Ca^{2+} as lime, or more commonly gypsum, to promote flocculation is a particularly important consideration (Shainberg et al., 1989).

When in excess, applied lime can also act as an amorphous cementing agent which can clog pores as well as physically binding adjacent particles together to form aggregates (Greene et al., 1978; Rimmer and Greenland, 1976). Thus, under field conditions the positive effect of lime is likely to be a result of a combination of cementing and flocculating actions. Hoyt (1981) observed that applications of CaCO_3 to two Canadian soils to raise soil $\text{pH}_{(\text{water})}$ into the range of 5.5 - 6.5 caused a major shift in distribution of dry aggregates towards coarser fractions, increased resistance of soils to compression and increased rapeseed plant emergence. The flocculating and coagulating effects of added lime appeared to be responsible for the improvement in soil physical condition. Similarly, large lime applications (e.g. 50t ha^{-1}) are traditionally applied to temperate clay and loam soils used for continuous arable crop production (i.e. soil organic matter levels are low) in Europe (Davies and Payne, 1988). This is believed to make them easier to cultivate and work. The reason for this is probably the cementing action of lime itself and that the slow dissolution of lime

maintains high soil solution Ca^{2+} concentrations thus favouring flocculation.

Liming acid soils results in the precipitation of exchangeable Al as amorphous, positively charged hydroxy-Al polymers (Haynes, 1984). Hydroxy-Al polymers are strongly sorbed on clay surfaces and thus reduce the negative potential on the surfaces. They are therefore excellent flocculants of soil colloids (Oades, 1979; Rengasamy and Oades, 1978) and their addition to clay systems greatly improves flocculation (Goldberg and Glauig, 1987; Gu and Doner, 1993). A reduction in the swelling and slaking of clays following precipitation of Al as hydroxy-Al onto clay minerals has been observed by a number of workers (El Rayah and Rowell, 1973; El-Swaify and Emerson, 1975; Oades, 1979).

If present in sufficient quantities, hydroxy-Al polymers can also act as cementing agents, bonding soil particles into aggregates. Oades (1979) showed that addition of hydroxy-Al cations to kaolinite caused marked reductions in surface areas of clays, a result indicating that cementation of fine particles had occurred. The increased contact between particles through the cementing action of Al hydroxide resulted in the formation of strong, water-stable aggregates. The flocculating and cementing actions of hydroxy-Al polymers are thought to have a significant effect in improving aggregation when acid soils, initially high in exchangeable Al, are limed (Castro and Logan, 1991; Roth et al., 1986).

3. Organic matter inputs and soil biological activity

Soil organic matter content and soil biological activity are intimately linked with soil aggregation and soil structural condition. Lime applications are known to have short-term effects in stimulating soil biological activity whilst it is also likely that liming will have long-term effects in increasing soil organic matter content.

a) Short-term effects

Short-term effects of liming on soil microbial activity have been recorded in both field (Edmeades et al., 1981) and laboratory (Badalucco et al., 1992; Haynes and Swift, 1988) experiments. Characteristically, the microbial population shifts from fungi to actinomycetes to bacteria as pH increases although acid tolerance of individual species varies widely. A temporary increase in microbial activity (i.e. flush of

activity) following lime additions to acid soils is well documented (Haynes, 1984).

Liming has been reported to increase microbial biomass content, soil respiration rate (CO_2 evolution), the microbial metabolic quotient (microbial respiration per unit biomass), soil enzyme activity (dehydrogenase, sulphatase and protease activity) and net mineralization of soil organic N and S (Badalucco et al., 1992; Edmeades et al., 1981; Haynes and Swift, 1988). These short-term effects of liming in causing a flush of microbial activity will have two opposing (but as yet unreported) effects on soil aggregation. Increased microbial activity could cause an increase in aggregate stability. The microbial biomass produces extracellular gelatinous polysaccharides which act as binding agents in soils (Burns and Davies, 1986; Cheshire and Hayes, 1990). In addition, fungal hyphae can form a network of enmeshing hyphae which also promotes aggregation (Burns and Davies, 1986). However, the accompanying increased mineralization and loss of labile soil organic matter would tend to reduce aggregate stability. Indeed, in the first year after application, Chan and Heenan (1996) found that liming resulted in an initial decrease in soil organic C content and aggregate stability but an increase in microbial biomass C content (since liming initially promoted C mineralization). However, a beneficial effect of lime on aggregate stability was evident after only 1.5 years. Further research to establish the exact relationship between the short term effects of liming on microbial activity and soil aggregation is certainly warranted.

b) Long-term effects

Liming could well have indirect effects on soil physical properties through its effect on increasing crop growth, soil organic matter content and thus background soil biological activity. Such effects are often cited as a major cause of improvements in soil tilth measured following liming (Baver, 1956; Roth and Pavin, 1991). Even so, there are few, if any, studies where a causal link between the effects of liming on soil organic matter content and soil physical properties has been established. Indeed, there appear to be no reports from long-term liming experiments where measurements of changes in soil organic matter content have actually been reported.

Reports from long-term fertilizer experiments do, however, show that in the long-term (i.e. >10 yrs) the increased yields resulting from fertilizer applications result in increased returns of organic matter to the soil

and a higher soil organic matter content than where no fertilizer is applied. It seems likely that long-term lime applications would have a similar effect. The reason for such an ascertainment is outlined below.

The major reason for liming acid soils is to improve crop growth and yields. The positive effects of liming usually occur through amelioration of Al and sometimes Mn toxicity and/or alleviation of Ca deficiency. Al toxicity is characterized by reduced top and particularly root growth. Liming can cause a large increase in root and top growth and an increase in the returns of C to the soil in the form of dying roots and decaying crop residues. In the long-term, these effects may well contribute to an improvement in soil structure (Haynes, 1984) because they will result in an increase in soil organic matter content.

For example, increased root growth and activity will improve soil aggregation. Large quantities of organic material are supplied to soils from roots. The major source of material is through normal growth and senescence of root segments and root hairs (Newman, 1985) but living roots also exude a range of organic substances (Oades, 1978). As a result of deposition of C, a large active microbial biomass develops in the rhizosphere. As already noted the microbial biomass produces polysaccharide binding agents (Burns and Davies, 1986; Cheshire and Hayes, 1990) and, in addition, roots, root hairs and vesicular arbuscular mycorrhizae (VAM) associated with roots can have an enmeshing effect forming a three-dimensional network which helps hold soil particles together to form stable aggregates (Tisdall, 1991; Tisdall and Oades, 1982). As plant residues decay soil humic substances are produced. These complex polymeric molecules are central to the formation of stable soil aggregates (Hayes and Swift, 1990) and are synthesized by the decomposer microflora during the decomposition process. Thus, the long-term effects of liming may well be to increase soil organic matter content by increasing root and top growth and thus inputs of organic residues to soil. As a result soil physical conditions, particularly soil aggregation and aggregate stability, are likely to improve. There is a need to examine such relationships on existing long-term liming trials. At present, the long-term effect of liming on soil organic matter status and soil physical properties is a matter for speculation.

c) Soil faunal activity

As well as influencing microbial activity, liming can also increase the size and activity of earthworm pop-

ulations. Most earthworms in temperate agricultural soils prefer a pH of around 7 although the sensitivity of individual species varies with some species (e.g. *Apporectodea caliginosa*) being particularly sensitive to acid soil conditions (Springett and Syers, 1984). Liming has often been shown to increase earthworm numbers (e.g. Stockdill and Cossens, 1966) and this is primarily a response to increasing pH rather than added Ca (Buckerfield and Doube, 1993; Springett and Syers, 1984). At low pH values, earthworms may not only be less numerous but also can go into diapause more rapidly upon the onset of dry conditions (Doekson and van Wingerden, 1964).

A lime-induced increase in earthworm activity may well have significant effects on soil structure. For example, earthworms ingest substantial quantities of soil and organic debris, mix them together and their casts may form the foundation for many stable aggregates particularly in pasture soils (Lee, 1985; Lee and Foster, 1991). Through their burrowing actions earthworms can also be particularly important in increasing soil macro porosity (Lee and Foster, 1991). Although liming has been shown to significantly increase earthworm numbers and activity, the consequent effects on soil aggregation and macroporosity have yet to be investigated and documented. The interaction between liming, earthworm activity and soil physical properties is certainly an area of applied soil ecology where there is scope for further research.

Fertilizer additions

The main nutrients applied routinely as fertilizers to agricultural soils are N, P and K. Applications of specific fertilizer materials (e.g. phosphatic fertilizers and NH_4^+ - containing or forming materials) can affect soil condition by influencing flocculation - dispersion and/or coagulation phenomena. However, the major effect of fertilizer applications on soil physical properties is to improve crop yields, increase organic matter returns and raise soil organic matter levels compared with unfertilized crops.

1. Physico-chemical effect of added phosphate

Several workers have documented changes in soil physical properties following additions of phosphatic fertilizer materials to soils (Lutz et al., 1960; Thein, 1976; Yeoh and Oades, 1981a, b). For example, approximately one year after initiating several phos-

phate trials (base rate = 150 kgP ha⁻¹) on North Carolina podzolic soils Lutz et al. (1960) observed that the P-treated plots were moist, loose and easy to plough whereas control plots were hard, dry and very difficult to plough. Measurements confirmed that P-treated plots had a lower bulk density and a higher soil moisture content throughout the growing season. Subsequent laboratory studies (Lutz et al., 1966) showed that additions of P to samples favoured flocculation of soil colloids and increased the water holding capacity of the soils.

The most likely explanation for such a phenomenon is that addition of P to acid soils results in the precipitation of Al as insoluble Al phosphates (Haynes, 1984). Such Al phosphates can act as flocculating and cementing agents in a similar way to hydroxy-Al compounds (see above). A significant effect of added phosphate through such a mechanism is only likely to occur on acid soils containing high levels of soluble and exchangeable Al and where relatively high rates of fertilizer phosphate are applied. In the vast majority of such cases it would be preferable from both an agronomic and economic viewpoint to apply lime and precipitate the Al as hydroxy Al compounds prior to application of fertilizer-P (Haynes 1982, 1984). This would reduce the rate at which costly phosphate fertilizer need be applied and increase fertilizer P use-efficiency by the crop.

A number of workers have investigated the use of phosphoric acid as an agent for promoting aggregate stability in soils (e.g. Thein, 1976; Yeoh and Oades, 1981b). Additions of phosphoric acid can increase aggregate stability where other phosphatic fertilizers have no effect. This is because its addition lowers soil pH and solubilizes soil Al associated with clay minerals which then subsequently precipitates as Al phosphate (Yeoh and Oades, 1981a, b). The Al phosphate forms an interstitial cement which binds aggregates together. Thein (1976), for example, found that whilst added phosphoric acid (applied from 50 - 220kgP ha⁻¹) markedly increased the aggregate stability of a soil through five drying and rewetting cycles, the addition of the same rate of P as triple superphosphate or ammonium polyphosphate had no measureable effect.

Addition of phosphoric acid to soils has been shown to effect soil physical conditions in a number of ways. Yeoh and Oades (1981b) showed that the water stable aggregates resulting from addition of phosphoric acid to soils led to higher porosities and water holding capacities and lower bulk densities than untreated soils. Phosphoric acid additions can also reduce the hardness

of soils as measured by modulus of rupture (Lutz and Pinto, 1965) and increase soil friability as measured by a decrease in aggregate tensile strength (Utomo and Dexter, 1981). Robbins et al. (1972) also found that additions of phosphoric acid reduced surface crusting in a calcareous soil. Applied phosphoric acid dissolved free CaCO₃ with the subsequent formation of calcium phosphate cementing agents.

Phosphoric acid has been used to improve the properties of soils for engineering purposes (Ingles and Metcalf, 1972) but has not found general use because it is expensive and corrosive. Similarly, although spraying phosphoric acid onto the soil surface can sometimes improve soil physical condition and increase crop yields it does not often produce reliable economic returns (Yeoh and Oades, 1981b).

2. *Dispersing effect of added ammonium*

Applications of NH₄⁺ - containing or forming fertilizers have sometimes been shown to have an adverse effect on soil aggregation. When the monovalent NH₄⁺ ion accumulates in soils in large amounts it can become a dominant exchangeable cation and, like Na⁺, it favours dispersion of soil colloids.

In most situations, NH₄⁺ is rapidly nitrified to NO₃⁻ within a period of several weeks so that any dispersing effect of NH₄⁺ is likely to be only temporary. However, where conditions are unfavourable for nitrification (e.g. low soil pH, high levels of accumulated NH₄⁺, low soil moisture content) NH₄⁺ may accumulate in the soil (Haynes, 1986). Thus, Pillsbury (1947) found a significant reduction in infiltration rate following application of (NH₄)₂SO₄ to surface irrigated Californian soil. Similarly, Fox et al. (1952) broadcast-applied NH₄NO₃ on the surface of an eroded Nebraska soil in late autumn and found that low soil temperatures inhibited nitrification. Ammonium accumulated in the soil until late spring and as a result of its long persistence, dispersion and surface crusting occurred. Crusting was observed at N rates as low as 20 kgN ha⁻¹. Aldrich et al. (1945) also observed dispersion after continual application of (NH₄)₂SO₄ to a soil. These applications resulted in a pronounced depression in soil pH and this, in turn, inhibited nitrification and favoured accumulation of applied NH₄⁺ in the soil.

From the above discussion it seems that it is unwise to surface apply NH₄⁺ - fertilizers to poorly-aggregated, fine textured soils with low organic matter content which are subject to dispersion particu-

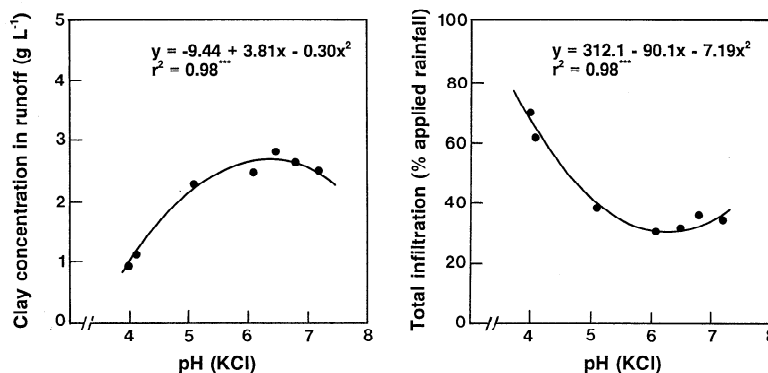


Figure 1. Relationship between $\text{pH}_{(\text{KCl})}$ and clay dispersion and total infiltration for a Brazilian Oxisol treated with increasing rates of lime and incubated for six weeks. Redrawn from Roth and Pavan (1991).

larly when climatic conditions are unfavourable for rapid nitrification. However, in most situations application of NH_4^+ in the field is unlikely to affect structural stability unfavourably because too small a proportion of the soil volume is affected for too short a time. Indeed, long-term experiments investigating the effects of annual applications of NH_4^+ fertilizers on soil physical properties have revealed no significant effects (Darusman et al., 1991; Intrawech et al., 1982). Intrawech et al. (1982) measured saturated hydraulic conductivity, penetrometer resistance, bulk density, soil water content, water stable aggregation and compactability and found no significant difference between 10 years of annual applications (224 kgN ha^{-1}) of a range of NH_4^+ fertilizers and control plots.

3. Organic matter inputs and soil biological activity

Fertilizer applications are made to soils in order to maintain or improve crop or pasture yields. The increased plant biomass produced by fertilizers results in increased returns of organic material to the soil in the form of decaying roots, litter and crop residues. This is demonstrated by the results of the Hoosfield continuous barley experiment (Figure 2) where the plot which has received annual N, P, K fertilizers has equilibrated to an organic matter content that is 15% higher than the unfertilized treatment. Similarly, on a long-term experiment at Broadbalk (Rothamsted) which has grown continuous wheat since 1843, there is a strong linear correlation between the amount of fertilizer N applied annually (ranging from 0-200 kgN ha^{-1}) and the quantity of organic C accumulated in the soil (Edwards and Lofty, 1982; Johnston, 1969). Thus, the increasing rates of N resulted in increasing crop yields and

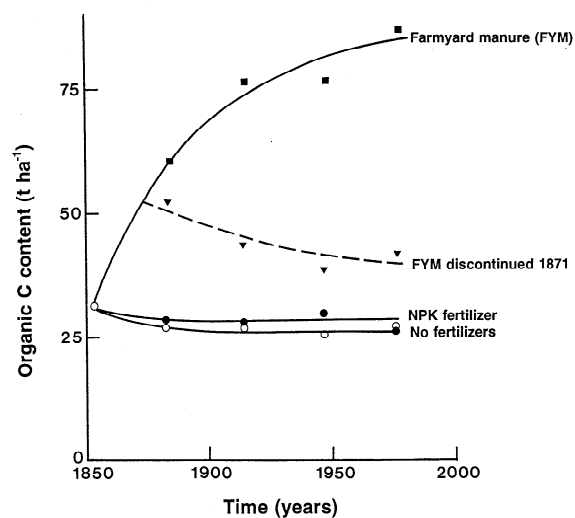


Figure 2. Changes in soil organic C content on the Hoosfield continuous barley experiment at Rothamsted. Treatments consist of: no fertilizer applied, NPK fertilizer applied annually, farmyard manure (FYM) applied annually at 35 t ha^{-1} and FYM applied 1852-1871 and none since. Redrawn from Johnston (1986).

increasing amounts of organic matter being returned to the soil.

Similar findings have been observed under pasture (Haynes and Williams, 1992a, b; Nguyen and Goh, 1990). The pattern of soil organic matter accumulation over a 38 year period after an arable field at Winchmore (New Zealand) was sown-down in pasture is shown in Figure 3. Accumulation of organic matter was particularly rapid during the initial 10 years. Organic matter inputs under pasture arise from senescing plant tops and roots, exudation of organic compounds from pasture roots, turnover of the large microbial biomass in

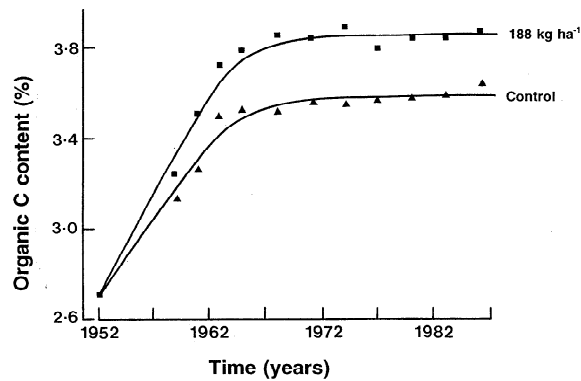


Figure 3. Changes in soil organic C content over a 38-year period of pasture development with no fertilizer applied (control) or 188 kg superphosphate ha⁻¹ applied annually. Redrawn from Nguyen and Goh (1990).

the pasture rhizosphere and return of ingested organic material by grazing animals in the form of dung. Annual additions of superphosphate at a rate of 188 kg ha⁻¹ increased mean pasture dry matter yields over the 38-year period from 4 to 12 t ha⁻¹ (Haynes and Williams, 1992b). This increased dry matter production resulted in greater organic matter inputs to the soil and thus the equilibrium organic matter level reached was higher with superphosphate applications (Figure 3).

The larger organic matter returns with fertilizer additions can stimulate soil biological activity. For example, after about 130 years on the Broadbalk experiment at Rothamsted biomass C content had equilibrated to 128 $\mu\text{g C g}^{-1}$ with no fertilizer applications and 189 $\mu\text{g C g}^{-1}$ with annual applications of N, P, K, Mg and Na (Sparling, 1985). On this experimental site, earthworm numbers and biomass have increased in proportion to the amount of N applied annually (Edwards and Lofty, 1982) as have soil organic C levels (see above). Several other studies have also shown that under arable cropping systems long-term fertilizer applications increase microbial numbers and biomass and the activity of some enzymes in soils (Dick, 1992; Khan, 1970; Martyniuk and Wagner, 1978; Schnürer et al., 1985). Similarly, under grazed pasture on the Winchmore long-term experiment (Figure 3), annual applications of superphosphate at 188 kg ha⁻¹ for 38 years have resulted in an increase in biomass C content and protease and arylphosphatase enzyme activities compared with unfertilized control plots (Fraser et al., 1994; Haynes and Williams, 1992b). Earthworm numbers and biomass have also increased (Fraser et al., 1994).

Unfortunately, although some studies have documented the long-term effects of fertilizer applications on increasing soil organic matter content and soil biological activity, few workers have measured the consequent effects on soil physical properties. As noted in a previous section on liming, increased organic matter inputs and stimulation of soil microbial and faunal activity will favour improved soil aggregation and increased soil porosity. A slow increase in soil organic matter content with long-term fertilizer additions will certainly favour improved soil physical conditions. Increasing soil organic matter content characteristically leads to a decrease in bulk density and surface crusting and an increase in water holding capacity, macroporosity, infiltration capacity, hydraulic conductivity and aggregation. These aspects are discussed in detail in a following section dealing with the effects of manure additions on soil physical condition.

An example of the effects of long-term NPK fertilizer applications on soil organic C content and some soil physical properties on the long-term Askov experiment in Denmark is shown in Table 1. The site is under a predominantly arable crop rotation that includes winter cereals, root crops, spring cereals and grass/legume mixtures. After 90 years, the plots receiving annual applications of NPK fertilizers had an 11% higher organic C content than the control plots. The higher organic matter content resulted in the soil having a higher cation exchange capacity (CEC). It is interesting that the CEC of organic matter derived from NPK applications (5600 $\text{m mol}_c \text{ kg}^{-1}$ of soil organic matter) was greater than that derived from addition of farmyard manure (3810 $\text{m mol}_c \text{ kg}^{-1}$ of organic matter). It appears that the soil organic matter formed due to fertilizer-induced crop yield increases (and thus increased organic matter returns) is of a more aromatic nature (and thus has a higher CEC) than that formed due to farmyard manure addition (Christensen, 1988; Schjønning et al., 1994). The increase in organic matter content induced by NPK applications resulted in a decrease in measured soil bulk density and a concomitant increase in total porosity with a tendency for an increase in the volume of pores in all size ranges (Table 1).

There are several other examples where long-term fertilizer applications have been reported to improve soil physical conditions. For instance, in an 11-year experiment, Chawla and Chabra (1991) found that annual applications of N and P resulted in increases in infiltration rate, hydraulic conductivity and percent water stable aggregates and decreases in bulk density

Table 1. Effect of annual NPK fertilizers and farmyard manure (FYM) on organic C, CEC, bulk density and porosity of the 0-20 cm soil layer after 90 yr of cultivation and cropping in a rotation of winter cereals, root crops, spring cereals and grass/legume mixtures.

Treatment	Organic C (g kg ⁻¹)	CEC (m molc.kg ⁻¹)	Bulk density (Mg m ⁻³)	Porosity (m ³ m ⁻³)			
				<0.2 um	0.2-30um	>30um	Total
Control	10.7	99.3	1.64	0.074	0.177	0.129	0.380
NPK	11.9	111	1.58	0.078	0.185	0.136	0.399
FYM	13.9	116	1.57	0.080	0.197	0.126	0.403
LSD (P≤0.05) ^a	0.8	10.9	0.04	0.002	0.014	NS ^b	0.015

^aLeast significant difference.

^bNot significant

Data from Schjøning et al. (1994).

and water-dispersible silt and clay. Under continuous spring wheat on the Canadian Prairies, Nuttall et al. (1986) in a 25-year study noted that annual applications of N and P improved soil aggregation. Similarly, Darusman et al. (1991) found that 20 years of annual applications of N to arable land had resulted in significant increases in aggregation in the 6-14 cm soil layer although bulk density and compactability were unaffected.

Organic manures

Applying organic manures at agronomic rates for plant nutrient supply was a traditional agricultural practice. In addition to supplying nutrients, the applied manure was known to have beneficial effects on soil physical properties (Lemmermann and Behrens, 1935; Low, 1954). Over the last decade the effects of organic manures and wastes on soil properties has received renewed attention. This is because there has been increased interest in disposal of wastes (e.g. animal manure from feedlots and housed livestock, composted municipal wastes and sewage sludge) at rates far in excess of traditional agronomic rates.

1. Soil organic matter content

Numerous studies in both temperate and tropical regions have shown that large increases in soil organic matter content can be achieved by adding organic manures and wastes to soils (Khaleel et al., 1981; Lal and Kang, 1982; Sanchez et al., 1989). An increase in organic C content when farmyard manure (FYM) was applied to an arable soil (cropped continuously with cereals) each year at 35 t ha⁻¹ is illustrated in Figure

2. There was an exponential increase in organic C content over a 140 year period and it is now approaching a new equilibrium level at an amount over three-times that of unfertilized soil.

The amount of organic matter accumulated in the soil per tonne of organic material applied can vary greatly depending on its ease of decomposition. As a result, no simple relationship exists between C application rates through waste application and the observed net increase in soil organic C content (Khaleel et al., 1981). Sauerbeck (1982) showed that when a range of organic materials was added to soil, accumulation of soil organic C increased in the order green manure < straw < fresh FYM < composted FYM. Similarly, Johnston (1975) showed that the increase in soil organic C per tonne of organic matter added was greater for composted than fresh material. For example, after 8 and 25 years of biennial applications of organic materials the percentage of organic material added that remained in the soil amounted to 44 and 25% respectively for FYM and 62 and 31% respectively for composted vegetable waste. These differences relate to the amount of decomposition that has occurred prior to the manures being added to the soil. During composting there is much breakdown of easily decomposable organic material and consequent loss of CO₂. As a result, when composted material is added to the soil it is relatively more resistant to further breakdown than fresh material.

In arable systems, which favour organic matter decomposition, the soil organic C content begins to decline as soon as manure applications cease (Johnston, 1975). As shown under continuous barley (Figure 2), soil organic C content began to decline as soon as annual additions of FYM ceased in 1871. Even so, 104 years after the last addition the plot contained more

organic C than did plots not receiving organic manures. This demonstrates the great stability of soil humic material. When organic materials as diverse as FYM and sewage sludge were added to soil and allowed to equilibrate for some years, Johnston (1975) showed that the accumulated soil organic matter decayed at the same rate over a subsequent 20-year period. This suggests that soil humic materials formed during degradation of diverse organic waste materials are very similar in nature and therefore degrade at similar rates.

Since addition of manure to soil means the addition of a source of available C, it is not surprising that soil microbial activity is characteristically increased. Indeed, many workers have shown that continual additions of farmyard manure usually increase the size of the microbial biomass (Martyniak and Wagner, 1978; McGill et al., 1986; Schnürer et al., 1985) and stimulate enzyme activities (Dick et al., 1988; Khan, 1970; Verstraete and Voets, 1977). Due to the provision of an additional food source, additions of organic manures to soils have also been shown to greatly increase earthworm populations (Andersen, 1983; Edwards and Lofty, 1982; Standen, 1984). As already noted, such increased soil biological activity will tend to have positive effects on both soil aggregation and macroporosity.

2. Improvement in soil physical conditions

Since soil organic matter content and soil biological activity increases when manures are applied to soils it is not surprising that soil physical properties also typically improve (Sanchez et al., 1989). Indeed, direct relationships have been established for changes in bulk density and water holding capacity as a function of net increases in soil organic C caused by organic waste applications (Khaleel et al., 1981; Metzger and Yaron, 1987).

Decreases in bulk density as a result of waste additions are due to a dilution effect caused by mixing of the added organic material with the more dense mineral fraction of the soil. Based on the data from 12 different workers, 21 soil types, 7 waste types and 8 crop types Khaleel et al. (1981) calculated a highly significant linear regression ($r^2 = 0.69$) between observed increases in soil organic C as a result of waste applications and the percentage reduction in bulk density. The relationship between soil organic matter content and bulk density on a soil amended with increasing rates of poultry manure is shown in Figure 4.

The water holding capacity of soils at both field capacity and wilting point is generally increased by

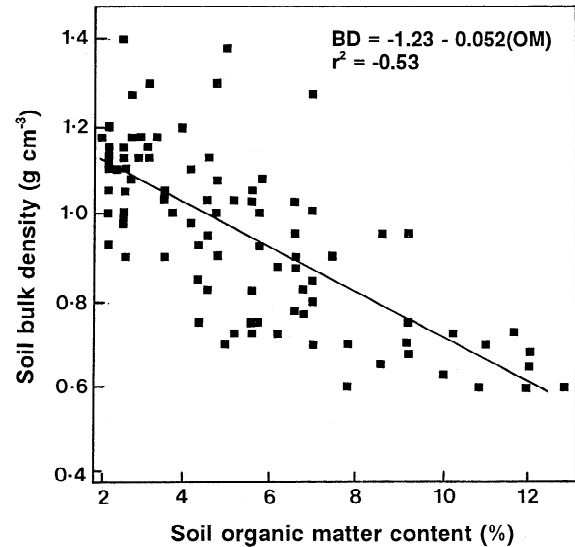


Figure 4. Relationship between bulk density and organic matter content of soil from experiments where poultry manure has been applied to soil at increasing rates. Redrawn from Weil and Krootje (1979).

additions of organic wastes. As a result, the available water holding capacity is often not greatly affected. Water holding capacity is controlled primarily by the number of pores and their pore size distribution and the specific surface area of soils. Because of increased aggregation, total pore space is typically increased by organic matter additions (Kladivko and Nelson, 1979; Sanchez et al., 1989; Tiarks et al., 1974). Furthermore, as a result of decreased bulk density, pore size distribution is altered and the relative number of small pores (i.e. $< 30 \mu\text{m}$ diameter) increases especially for coarse textured soils (Khaleel et al., 1981; Pagliai et al., 1981). An increase in total porosity and the relative volume of pores $< 30\mu\text{m}$ diameter after 90 years of annual FYM application is shown in Table 1. An increased water holding capacity at low tensions such as field capacity is primarily due to the increased number of small pores. At higher tensions close to wilting point, nearly all pores are filled with air and the moisture content is determined by the surface area and the thickness of water films on these surfaces (Khaleel et al., 1981). Following addition of organic matter, specific surface area increases resulting in increased water holding capacity at higher tensions (Gupta et al., 1977).

Where earthworm activity is increased by waste applications, macroporosity may also be increased. Weil and Krootje (1979), for example, showed that

heavy applications of poultry manure resulted in greatly increased earthworm activity during spring and summer. As a result, infiltration rates in autumn were considerably larger in manured than control plots due to the large number of surface-connected burrows that had been formed.

Since soil organic matter is central to the formation of stable aggregates there is normally a close relationship between soil organic matter content and water stable aggregation in soils (Chaney and Swift, 1984; Haynes et al., 1991). Thus, additions of organic wastes to soils normally cause an increase in the size and amount of water stable aggregates (Ekwue, 1992; Hafez, 1974; Tiarks et al., 1974; Weil and Kroontje, 1979; Williams and Cook, 1961).

The degree of organic matter decomposition prior to adding wastes to soils can have a significant influence on their effect on aggregation. Many workers have demonstrated the value of adding easily decomposable C sources (e.g. green manure) to soils or artificial aggregates (Griffiths and Jones, 1965; Low, 1954; Monnier, 1965; Rennie et al., 1954). After a brief lag phase there is a flush of microbial growth with a concomitant increase in physical entanglement by fungal hyphae and the production of extracellular polysaccharides capable of linking soil particles together. There is therefore a rapid rise in aggregate stability. Usually, this improved stabilization is only temporary since the microbial population rapidly declines and hyphae and polysaccharides decompose so that the newly-formed interparticle links become severed. By contrast, the addition of well-decomposed, composted material induces a slow and more steady increase in aggregate stability (Monnier, 1965) since the organic matter consists mainly of humic substances which are relatively stable binding agents.

Because of the increases in porosity and aggregate stability induced by application of organic wastes, other soil physical properties can be improved. These include decreased surface crusting (Epstein et al., 1976; Mazurak et al., 1975), a decrease in the amount of soil particles detached by raindrop impact (Mazurak et al., 1975), increased infiltration capacity and hydraulic conductivity (Cross and Fischbach, 1972; Ekwue, 1992; Tiarks et al., 1974; Weil and Kroontje, 1979) and decreased runoff volumes (Hensler et al., 1970; Young and Mutchler, 1976). It should, however, be noted that applications of high rates of organic wastes to soils can sometimes have detrimental effects on soil physical properties. This aspect is discussed below.

3. *Detrimental Effects*

Detrimental effects of adding large quantities of organic manures to soils have included surface crusting, increased detachment by raindrops and decreased hydraulic conductivity (Cross et al., 1973; Mazurak et al., 1975; Olsen et al., 1970; Tiarks et al., 1974; Weil and Kroontje, 1979). The primary reason for this soil structural breakdown is the high content of monovalent cations (Na^+ and particularly K^+) in animal waste material. In addition high concentrations of NH_4^+ may also accumulate through mineralization of organic waste N. When waste is applied at high rates (e.g. $> 100 \text{ t ha}^{-1}$) these cations may become the dominant exchangeable cations and dispersion of soil colloids can occur. Indeed, at high rates of waste application, soil salinity levels can increase to the extent that germination of salinity-sensitive crops is inhibited (Epstein et al., 1976). Excess salts will tend to be leached by rainfall and irrigation water thus reducing potential salinity and soil physical problems but contributing to pollution of groundwater. Tiarks et al. (1974) found that when cattle feedlot manure was applied to soil in spring at $90\text{-}360 \text{ t ha}^{-1}$ it caused decreases in hydraulic conductivity when measured in late summer. However, leaching over winter reduced salt content to levels where there was no detrimental effect on soil physical conditions. In fact, Tiarks et al. (1974) suggested that the increased organic matter content and enhanced aggregation in manure-treated plots may have promoted leaching of excess salts.

Another problem sometimes noted at high rates of manure application is that the soil can tend to take on water-repellent properties (Olsen et al., 1970). This is thought to be due to production of water-repellent organic substances by fungi involved in decomposition of the manure (Weil and Kroontje, 1979). Olsen et al. (1970) observed that addition of dairy manure to an acid loamy sand caused a reduction in field capacity due to the presence of waxy, water-repellant substances in the soil profile. Weil and Kroontje (1979) found that after 5 years of heavy applications of poultry manure to a soil, manured plots were more moist in the plough layer especially in the spring due to a perched water table at 20 cm depth. This was caused by a water-repellent ploughsole layer of partially decomposed manure which was ramified with white fungal mycelia. They concluded that incorporation of manure by means other than a mouldboard plough might avoid creation of such an organic ploughsole layer.

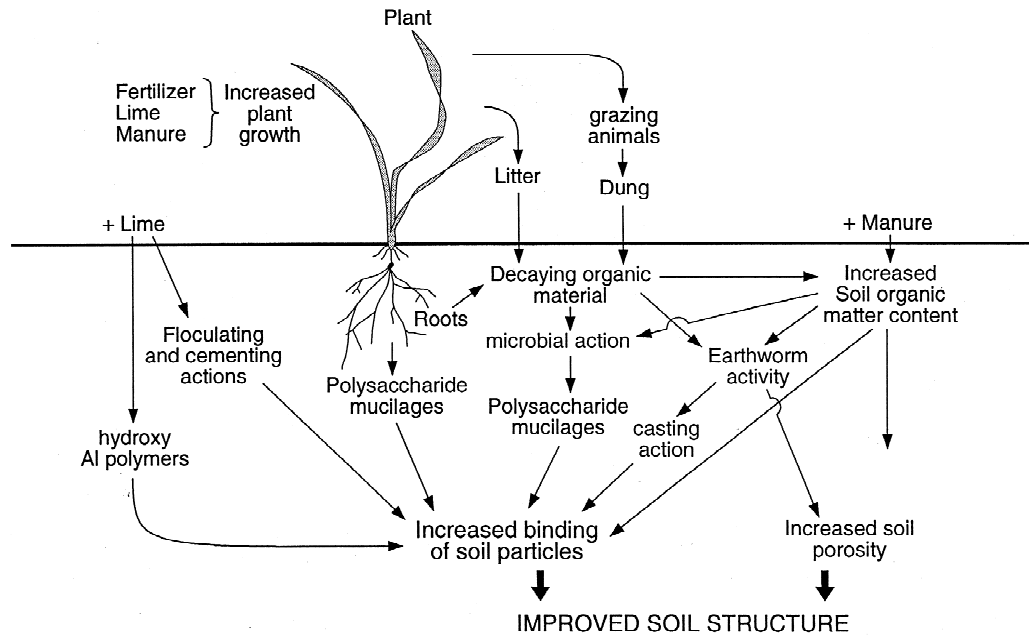


Figure 5. A conceptual model of the major effects that fertilizer, lime and manure have on improving soil aggregation and soil structural condition.

Conclusions

A conceptual model summarizing the major effects that fertilizer, lime and manure have on improving soil aggregation and soil structural condition is presented in Figure 5. The model summarizes the processes that have been discussed throughout the paper and demonstrates the complex interactions that are possible. There is a surprising lack of information on the relative importance of many of these processes. There is considerable scope to investigate some of these processes on the long-term lime and fertilizer experiments that exist throughout the world. For example, whilst some such studies have demonstrated an increased soil organic matter content resulting from long term fertilizer applications, few have extended this to determine whether soil physical conditions have improved.

The relative importance of the different pathways shown in Figure 5 will differ depending on the particular circumstances and the time-scale being considered. For example, short-term effects of lime (i.e. <1 year) are likely to be the result of physico-chemical effects. On highly-weathered acidic tropical soils, where relatively low lime rates are applied to neutralize exchangeable Al (usually to raise $\text{pH}_{(\text{water})}$ to 5.3 - 5.6), precipitation of exchangeable Al as hydroxy-Al species will be the main factor improving soil structural

condition. Hydroxy-Al has flocculating and cementing actions. For temperate soils, with a higher initial pH and low levels of exchangeable Al, lime is often applied to raise soil $\text{pH}_{(\text{water})}$ to 6.0 or above. In such situations the flocculating effect of Ca^{2+} and the cementing action of lime itself are likely to be the dominant mechanisms in the short-term. In the longer-term, lime-induced increases in crop yields will result in greater input of organic material and a build-up in soil organic matter and soil biological activity both of which favour improved aggregate stability and increased porosity.

For fertilizer additions, short-term effects appear to be relatively rare. Their main effect is a long-term one through an increase in crop production with an attendant increase in soil organic matter content and soil biological activity. For organic manures the major effect is simply the addition of organic matter to the soil.

In recent years increased emphasis has been placed on the sustainability of agricultural systems. Sustainable soil management practices and the maintenance of soil quality are central issues to agricultural sustainability. The long-term positive effect of continual applications of fertilizer materials on soil organic matter content and soil physical conditions is an important,

although often neglected, factor that needs to be considered when contemplating sustainability.

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