MINISTRY OF AGRICULTURE, FISHERIES AND FOOD **CSG 15**

Research and Development

Final Project Report

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Project title	A national soil vulnerability based framework for the provision of farm specific guidance on the management of soil structure		
MAFF project code	**SP0305**		
Contractor organisation and location	Soil Survey and Land Research Centre Cranfield University Silsoe, Bedfordshire, MK45 4DT		
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Executive summary (maximum 2 sides A4)

Soil is a living medium, consisting of structural units (aggregates) composed of soil particles (sand, silt and clay) held together by roots, organic matter and soil organisms and separated by pore spaces. Structure results in part from the generation of biopores and fissures of different sizes and inter-connectivity by plant roots and soil biota. Many topsoils are fifty percent pore space by volume, but the pore size distribution and inter-connectivity vary greatly. Structure is essential for plant growth as it allows root penetration, soil aeration and the drainage of surface water into and through the soil. When soil is compacted the natural porosity is markedly reduced, so that in severe cases water and air movement and root development are restricted. This will frequently result in the soil surface being waterlogged during periods of wet weather, even though an under-drainage system may be present. Rooting will tend to be shallow, exploiting only a small volume of soil. This means that the crop will be more susceptible to shortages of nutrients and water during periods of dry weather. The protection of soil structure is therefore essential to the long-term productivity of land. This fundamental role is recognised in the UK Strategy for Sustainable Development (Department of the Environment, 1995).

Because of its responsibilities to sustain the farming community, to ensure food supplies and to protect the environment, MAFF advises farmers on good soil husbandry, including soil structure management, through *The Code of Good Agricultural Practice for the Protection of Soil* (MAFF, 1998). The research reported here will assist MAFF in achieving its objectives in relation to:

- supporting and sustaining a financially healthy farming community,
- ensuring adequate food supplies and maximising home food production,
- the protection of soil resources and the wider environment,
- encouraging greater diversity in soil fauna.

Shear strength measurements of field moist bulk soil have been compared to the shear strength of aggregates from the same bulk soil. These measurements require the development of specialised equipment to allow bulk soil within the topsoil to be sheared in such a way that the unloaded shear stress at failure could be determined and individual aggregates to be subjected to lateral shear using a translational shear technique.

An index has been proposed which is based on the normalised differences between the bulk and aggregate shear strength. We hypothesise that a value of unity is indicative of a well-aggregated, loose soil while a value of zero indicates that the soil is structureless.

Initial tests on two distinctly different soil types (sandy loam and clay loam) at Silsoe, Bedfordshire showed that significant differences ($p < 0.05$) between the indices for the two soils existed. In the late winter and early spring of 1999 following autumn cultivations the clay loam soil was found to have an average index of 0.41 while the sandy loam had a value of 0.26. This difference was attributed to the collapse of structure that was evident in the sandy loam soil and to a much lesser extent on the clay loam soil. Tests conducted on soils that had undergone different tillage practices showed that soil structural conditions following natural weathering of ploughed and loosened soil were not significantly different to those encountered in the minimally tilled soil. Measurements made on 18 different soil types under arable cultivation across arable England using modified torsional shear equipment for bulk strength measurements, showed that clay content was the dominant factor influencing the structure index.

It is suggested that strength measurements of this type provide insights into the vulnerability of soils to structure breakdown under natural weathering processes, but that the exact mechanisms are more complex than simple shear of bonds within the aggregate. They show that the equipment and methodology innovated as part of this project produce valuable data on the relative strengths of field soils and consequently the amount of effort required to move soils. It is a technique that has implications and use not just in agriculture but in land restoration schemes.

Micro-organisms have long been implicated in mediating soil structural ability, in particular fungi that may form and stabilise aggregates. Evidence suggests that tillage can have an influence over the degree to which certain microbes influence soil structural parameters. For instance, ploughing soil leads not only to the disruption of the soil mass, but also to the breaking up of fungal hyphae. Direct drilling, on the other hand, maintains structural integrity and fungal hyphae to a greater extent. Ergosterol, a phospholipid only found in live fungi, was chosen as an indicator of biological health. The rationale to choose fungi over any other microbial community was firstly, the ease, reproducibility and accuracy of the measurement when confined to one soil type; secondly, the fact that tillage has been shown to have the largest immediate effect on fungal populations.

A key feature of the main field site was that soil, initially under a long-term grass management regime, has been simultaneously turned over to a range of management regimes, within an area that is sufficiently small that all other factors may be assumed constant across the site. The imposed regimes vary in the degree of disturbance from zero (grassland) through limited (direct drilled) to substantial (conventional tillage).

The overall effect of nitrogen levels in the treatments was low, presumably because there was still a large legacy of the nitrogen from the grassland in all sites. However, the effect of physically disturbing the profile was profound, both for the viewpoint of the physical and biological processes and characteristics of the soil. The greater the degree of disturbance (taking grassland as zero disturbance, direct drilled as limited and conventional ploughing as high), the lower the microbial activity. This impacts directly onto the physical resilience and stability of the soil. The direct drilled soil samples appeared to be more friable than the ploughed samples. Increasing nitrogen levels appeared to reduce friability for most of the ploughed and direct drilled samples. The aggregates taken from permanent grassland showed the lowest friability.

Field assessments of topsoil structure from detailed profile descriptions held in LandIS and the SSLRC paper archive were compiled in a spreadsheet. Size of structural units shows no discrimination in organic carbon at the cultivated sites but there is a decrease from small to very large at the permanent grassland sites, with the highest carbon values being found in small strongly developed peds and the lowest in very large weakly developed peds. Total pore space and retained water capacity show an increase as structure improves and a decrease as the size of unit increases. They also show relationships with Regeneration and Stability Indices with an increase as the stability and rate of regeneration increase.

The more traditional methods of estimating the physical aspects of the soil showed little correlation with the biophysical properties, which brings into question the value of using such data in elucidating the mechanisms behind soil biophysical vulnerability or to predict events where the soil may be vulnerable in the future. However, this does not invalidate their use when considering aggregate and bulk strength where there are good statistical relationships. The Peerlkamp Index is shown to be a very valuable field assessment of structural development having a correlation with strength measurements as well as air capacity. The Structural Quality index is a useful measure of the success in creating a good seed bed if there is access to measurements, rather than assessments, of air capacity and available water capacity. The Stability and

Regeneration Indices then show how vulnerable to degradation is the “potential” structure and the length of time it will take to return to the optimum following damage.

If soil management advice is to be targeted, then the areas identified with more unstable topsoils and slowest recovery should be the primary targets for advice and further research as to the relation between carbon levels and structural stability, in particular the fraction of the carbon that is the cause of instability.

One of the primary objectives of this project is that farmers are provided with farm-specific guidance about soil structural management. Consequently any structural assessment recommended must be simple, rapid and accurate for it to be used confidently in the field by personnel who may not be particularly knowledgeable about identifying ‘good or bad’ structure at the present time. Systems of assessment that rely on soil collection and laboratory analysis will not fulfil this requirement. Use of the more ‘hands - on method’ such as the “Peerlkamp Index” together with the guidance on structural development and aggregate shape and size contained in new brochure can be used to address the need for a simple and rapid method.

Scientific report (maximum 20 sides A4)

1 Introduction

Knowledge, gained from research, of the factors that influence structure (Thomasson, 1978, 1982; Smith, 1987; Scholefield and Hall, 1985 and Alexandrou and Earl, 1997) has not been previously brought together with the wealth of spatial information on soils and climate. Research into the influence of microbiota on soil structure and aggregate strength has elaborated the processes involved but has not, until now, been translated in advice on the management of soil structure on farms. Better understanding of interactions between soil micro-organisms, soil structure and selected soil management programmes should improve farm-specific guidance to maintain soil quality and improve crop yields. Thus, this project also incorporates research into soil biology and microbiology, such that site and soil-specific advice on good soil structure management practice can be improved.

1.1 Soil structure definition

There is no universally agreed definition of ‘soil structure’ and, in particular, whether any collection of particles in uniform or close packing can be said to have a structure or not (Russell, 1973). The term ‘soil structure’, as used here, refers both to the arrangement of the soil aggregates and the spaces between them (Marshall, 1962) and their longevity. They can range in size from less than a millimetre to tens of centimetres.

Soil structure can conveniently be divided into two categories, micro and macro, depending on the scale that is being observed. Microstructure is concerned with the arrangement of particles within aggregates, as evidenced for instance by thin sections, whereas macrostructure refers to the arrangements of the aggregates themselves in the bulk soil. Edwards and Bremner (1967) proposed that soils consist of microaggregates (< 250 µm) bound into macroaggregates (> 250 µm). The formation of microaggregates has been shown to reduce erosion and increase soil moisture content. Specific mechanisms bind aggregates of different sizes and include electrostatic bonds, polysaccharide 'glues' and physical entanglement (Miller & Jazstrow, 1990, Tisdall & Oades, 1982). The micro-organisms responsible for many of the binding mechanisms are affected in turn by the structure and nutrient content of the soil, which can be altered by agricultural practices such as tillage.

The following sections are named and ordered according to the scientific objectives listed in the original project proposal. Tables, figures and references referred to in the text are included as Appendices 1, 2 and 3 respectively.

2 Classification of soil, climate and physiography

The soil classification used in England and Wales is summarised in Clayden and Hollis (1984). The definition and derivation of the climatic concepts of field capacity period and soil moisture deficit as they affect soil structure are discussed by Brignall and Rounsevell (1994).

3 Review of research and information

3.1 Introduction

The Strutt Report (MAFF, 1970b) reviewed evidence for soil structural degradation and more recently the Royal Commission on Environmental Pollution (1995) has indicated the need for research to underpin more detailed guidance to farmers on the management of soil structure. Research since the Strutt Report has developed the understanding of the physical, chemical and biological processes affecting structural development and the relationship between degradation and land management practices and soil characteristics (Edwards, 1984; Greenland, 1977; Newman and Thomasson, 1979; Soane *et al.*, 1981; Soane *et al.*, 1987; Young *et al.*, 1991 and Godwin and Leeds-Harrison, 1994).

Developments in agricultural machinery, such as greater tractor power, low-pressure tyres and the evolution of powered harrows, now allow greater management flexibility, but also opportunities for both improved soil protection and greater abuse depending on how that flexibility is exploited (Davies *et al.*, 1973). Research and practical experience has been gained from work in the field of soil restoration and creation and has highlighted the fundamental importance of soil biota and microbiota in soil structure development (Marinissen, 1994). Renewed interest in minimal cultivation and direct drilling is making farmers look more closely at their seedbeds.

3.2 Factors in the development of soil structure

Weathering and trafficking on a tilled surface may encourage structural collapse in vulnerable soils; indeed it is likely that all soils undergo such changes to some extent during a growing season. Thus, temporal changes to the relative difference between bulk and aggregate strength provide an indication of structural state. Whilst a considerable amount of work has been undertaken on investigations of soil bulk strength, rather less has been undertaken on aggregate strength. The literature indicates that no work has been undertaken on the relationship between aggregate and bulk strength for soils under agricultural field conditions. Part of the project has aimed at quantifying bulk strength and aggregate strength of field soils over time and under different tillage and soil management practices with a view to relating these data to structural vulnerability. In a field situation where the concern is structural degradation due to physical processes, soil cohesion is of most interest.

Figure 1 shows an arrangement of aggregates which comprise the micropore region, and the macropores which constitute the spaces between the aggregates in the bulk soil. While the arrangement of aggregates in Figure 1 may vary, the general view of macrostructure can be related to this diagram. The aggregates comprise collections of primary particles and small aggregations, but in such a way as to produce a recognisable unit. The bulk soil comprises an arrangement of these aggregates such that large spaces - referred to here as macropores - are left between them.

Any mechanical disturbance to the bulk soil is likely to have a greater affect on the macrostructure than on the microstructure. Disturbance may occur during mechanised field operations (tillage) and may involve compaction (when macroporosity decreases) or loosening (when macroporosity increases). Tillage may also deform or shear aggregates and the balance between one or other of these two effects on the macrostructure and microstructure depends on the state of the soil when the operation takes place. If the arrangement of aggregates is compacted then the bulk density of the soil will increase; loosening will have the converse effect. Density changes might thus be a measure of soil macrostructure but knowledge of the density of the aggregates themselves is also needed if information about the macrostructure is to be revealed.

In cases where the aggregates themselves are subject to breakdown because of some external force, then bonds between particles must be broken. Figure 2 shows the effects of aggregate breakdown on the macrostructure. The effect of this process is to infill the macropores, increasing the density of the soil and lowering its macroporosity. Very fine particles may move with water flowing in the soil so as to change the internal nature of the micropore region. There may be difficulty in distinguishing between changes in density brought about by these two distinctly different processes. It is clear that the distribution of pores within the aggregates and within the bulk soil will lead to particular effects on the internal processes within the soil.

3.2.1 Soil particle size

Soil particles can be divided into two broad classes based on their size. Clay particles are smaller than 2 µm and the non-clay particles are larger, with an upper limit of 2 mm, beyond which particles are classed as stones. The non-clay particles can be further divided into silt and sand. Clay particles have more impact on aggregate stability than non-clay particles, due to the fact that clay is chemically and physically reactive whereas non-clay particles are not. Silt has, however, been found to have some importance in aggregate stability due to substantial accumulation of organic matter within silt fractions.

3.2.2 Organic matter

Organic matter may increase structure stability through three types of cementing agents:

- Transient agents of microbial and plant derived polysaccharides that decompose rapidly
- Temporary agents including roots, hyphae and mycorrhizas
- Persistent agents of aromatic humic materials associated with amorphous iron and aluminium compounds as well as other polyvalent metal cations.

Polysaccharides are long, linear, flexible molecules that link particles by bridging gaps between them (Greenland, 1965, Theng, 1982). They are too small to connect one sand particle to another and need to interact with clay or with inorganic colloids in order to produce links. The most important sources of polysaccharides are those produced by microbes when organic materials are added to the soil and those associated with roots and the microbes in the rhizosphere. Although they are formed and decomposed rapidly they play an important role in structure stability at the macroscale. Their importance depends partly on management practices. The role of polysaccharides for the structural stability of a soil with high organic matter content is relatively less important than in a soil with a low organic matter content. Some polysaccharides might persist in the soil for many years as they associate with metal ions, tannins or become adsorbed to the clay surfaces thus protecting them from microbial attack.

Temporary binding agents also affect structure on a macroscale, their importance varying with management practices. Roots supply organic matter to the soil in the form of fine lateral roots, root hairs, sloughed-off cells from the root cap, dead cells, mucilages, lysates and volatile and water-soluble materials (Soper, 1959; Rovira and McDougall, 1967; Shamoot *et al.*, 1968, Martin, 1971; Dickinson, 1974; Oades, 1978).

Roots also act directly as binding agents by holding the soil particles together even after their death (Clarke *et al.*, 1967). Roots also stabilise aggregates by drying out the soil around them. This leads to a parallel orientation of the clay particles close to the root. They can also indirectly affect soil structure stability by increasing the amount of mesofaunal activity (Tisdall and Oades, 1982). Hyphae and fungi stabilise macroaggregates in the soil; also they grow in the relatively larger pores and bind the aggregates together.

Humic substances are probably derived from the resistant fragments of roots, hyphae, bacterial cells and colonies developed in the rhizosphere (Tisdall and Oades, 1982). They can be divided into three fractions, humin, humic and fulvic acids, based on their solubility in aqueous acids and bases. Each of these fractions is a heterogeneous mixture of compounds with a wide range of molecular weights and negative charges. It is very difficult to know which of the fractions, if any, play an important role in stabilising aggregates due to the difficulties in defining each fraction. However they play an important role in stabilising the microstructure of the soil as they interact with metal ions, oxides and hydroxides and other organic substances to form water-stable associations.

Many arable and grassland soils now contain less organic matter than 20 years ago (Department of the Environment, 1996; Loveland *et al.*, 2000) rendering them potentially more vulnerable to structural damage.

3.3 Factors in the development of macrostructure

The formation of large pedal masses in the soil (Figure 3) arises due to stresses, both internal and external, that are applied to the soil mass. These stresses arise due to changes in water status in the bulk soil micropore regions or due to externally applied forces as might occur in tillage operations. The key natural processes leading to the formation of macrostructure are:

- Swelling and shrinking
- Wetting and drying
- Freezing and thawing
- Root and invertebrate activity

3.3.1 Swelling and shrinking and wetting and drying

Swelling and shrinking occurs due to changes in water content in a soil that contains clay. Organic matter can also induce swelling and shrinking in a soil that does not contain clay but to a much lesser extent. These processes create a change in volume in the soil both on a micro and macroscale. As the volume of soil decreases, pores become larger as clay plates ‘push’ each other apart due to negative charge repulsion. These cracks probably form the initial faces of many peds. On smooth ped faces containing clay, sand and silt, the clay will move outwards before the sand and silt grains due to swelling. It seems as if the clay can not return to its initial position due to tension present in the soil water. Subsequent drying and shrinking would cause the soil to crack along the same lines, as this would require less energy. Horizontal movements that occur due to swelling and shrinking are made more obvious due to the cracks that appear on the surface, however vertical movements also occur. Vertical shrinkage causes the soil to break into prism like fragments, horizontal shrinking causes the prisms to become blocky.

3.3.2 Freezing and thawing

Most soils in the earth’s middle latitudes are subject to freezing and thawing. The effects of freezing and thawing are not as yet fully understood, but they can be compared to drying and wetting processes. Freezing affects aggregation by the expansion of water on changing to ice within the soil. In coarse textured soil, the water freezes but in fine textured soil there is movement of water towards freezing sites where ice lenses form. Water is held in micropores at a suction and does not readily freeze, some soils have been reported to contain unfrozen water at -40 to -50 °C. As temperatures drop, water is withdrawn from areas where it does not freeze easily and lenses form. Compression and heaving of the soil occurs as the ice lenses grow. Compression of the somewhat drier soil near the lenses helps aggregates to form in fine-textured soil but the pores created tend to collapse when thawing occurs (Kay *et al.*, 1985). During thawing the bottom layers tend to remain frozen longer than the top layers. The top layers become saturated whilst thawing and this can cause a complete loss of strength of the top layers.

The top layers might recover their strength as the desiccated layers below absorb the surface water (Miller, 1980). The effects of freezing and thawing depends however, as for wetting and drying, on the particle size distribution of the soil. The benefits to soil structure are present only in clays (Czeratski, 1971). The effect of freezing and thawing on clod strength is non-existent. The changes that farmers notice are due to changes in moisture content.

3.3.3 Roots and invertebrates

Many investigators have reported that legume crops benefit soil physical conditions. Measurements have shown increase in total porosity, number of large pores, water intake rates and root penetrability of soil layers permeated by legume roots. Significant changes in soil physical conditions can be expected from any type of root system only if the roots penetrate and thoroughly permeate a given soil layer. Batey (1988) summarises the results of many experiments carried out to assess the effects of different crops on soil structure as:

- Soil structure (as assessed by stability or porosity) can deteriorate under arable crop production and improve under grass.
- Organic matter levels increase slightly after each year of grass in rotation.
- Nutrient effects, particularly nitrogen, can be masked by the use of fertilisers.

It is probable, however, that the effects of cropping on macrostructure depend on the individual management regime.

Roots affect structure both by separating and compressing aggregates. They excrete substances that give stability to the pores they have created. If the root tip is impeded it tends to swell exerting a pressure of up to 1 Mpa and this causes the soil to crack in advance of the root tip. Roots have a drying effect on the soil. As they absorb water, they create shrink and swell effects to a greater depth than would occur in their absence.

Invertebrates affect macrostructure by creating large channels thus increasing porosity. The organic matter in the casts they leave behind in the channels usually stabilise them.

3.4 Role of fungi in soil stabilisation

Micro-organisms have long been implicated in mediating soil structural ability (Tisdall & Oades, 1982), in particular fungi that may form and stabilise aggregates (Tisdall, 1991). Evidence suggests that tillage can have an influence over the degree to which certain microbes influence soil structural parameters. For instance, ploughing soil leads not only to the disruption of the soil mass, but also to the breaking up of fungal hyphae. Direct drilling, on the other hand, maintains structural integrity and fungal hyphae to a greater extent (Tisdall, 1991).

MacGovern (2000) presents a detailed review of the role of fungi in soil stabilisation.

3.4.1 Microaggregate Stability

A prerequisite for water-stable aggregation is flocculation of clay particles - the first stage in the construction of a stable macroaggregate (Tisdall & Oades, 1982). Water-stable particles < 2 µm are often floccules where individual clay plates come together to form a mass. The clay plates are held together by van der Waal's forces, H-bonding and ionic bonds. The charges of ions associated with the surface of the clay are influenced by organic and inorganic materials which may increase or decrease the attraction between the particles (Tisdall & Oades, 1982). While flocculation appears to be largely an electrostatic phenomena, organic polymers may promote flocculation, and the stabilizing of larger aggregates involves cementing or binding agents which may be inorganic, organo-mineral associations or organic (Tisdall & Oades, 1982).

Water-stable aggregates 2-20 µm diameter consist of particles less than 2 µm diameter bonded together so strongly by persistent organic bonds that they are not disrupted by cultivation. This organic-rich fraction is often highly water-stable especially in Chernozem soils, where upward water movement due to evaporation prevents leaching of organic matter (Eyre, 1968) and in soils under old pasture (Tisdall & Oades, 1982).

Emerson (1959) suggested that parallel clay crystals are grouped together closely enough (about 0.1-1.3 µm apart) to behave in water as a unit called a *domain*. His model shows that organic matter stabilises the aggregate mainly by forming and strengthening bonds between domains and between quartz particles and domains, though the quartz particles may also be linked directly by organic matter (Tisdall & Oades, 1982). Several models have been proposed to describe the way in which individual mineral particles are held together to form water-stable aggregates of soil. It has been suggested (Tisdall & Oades, 1982) that particles < 20 µm diameter are bound into water-stable secondary particles 20-60 µm diameter and that these secondary particles in turn form larger soil aggregates. Tisdall & Oades (1982) state that aggregates 20-250 µm diameter consist predominantly of particles 2-20 µm, bonded together by various cements including persistent organic materials, crystalline oxides and highly disordered alumino-silicates.

Persistent binding agents are probably derived from the resistant fragments of roots, hyphae, bacterial cells and colonies developed in the rhizosphere; the organic matter is believed to be the centre of the aggregate with particles of fine clay sorbed onto it. Also included in this group are strongly sorbed polymers such as some polysaccharides and organic materials stabilised by association with metals (Tisdall & Oades, 1982). Stability is sometimes related better to free organic materials than to total organic carbon because this fraction acts as a substrate for microbial production of organic glues (Tisdall & Oades, 1982).

Fungi are often the largest component of the microbial biomass in arable soils (Beare *et al.,* 1997) constituting more than 50% of the microbial biomass and probably contributing more than bacteria do to the organic matter in soil (Tisdall & Oades, 1982). Although Hassink *et al.* (1993) indicate that fungi make up only a very small part of microbial biomass this may well be due to their measuring technique, which would have excluded all mycorrhizal fungi. The size and distribution of soil fungal populations are related to the quantity and quality of organic matter inputs and the method of soil tillage employed (Beare *et al.*, 1997)

3.4.2 Macroaggregate Stability

In the hierarchical model of soil aggregate formation proposed by Tisdall and Oades (1982), a major mechanism involved in the binding of microaggregates into macroaggregates is physical entanglement by roots and mycorrhizal hyphae. It was found that the lengths of roots colonised by mycorrhizal fungi within each root-size class, and extraradical hyphal lengths of mycorrhizal fungi were all highly correlated with the geometric mean diameter of water-stable soil aggregates (Miller & Jastrow, 1990). Although individual hyphae are not strong, the combined strength of all hyphae and fine roots, especially in a three dimensional network, holds particles more or less equally in all directions so that aggregates do not slake when wetted rapidly (Tisdall & Oades, 1982). The clay on the surface of the aggregates protects the roots and hyphae from microbial decomposition, but once the roots and hyphae die, the network is broken by fauna or tillage, and the macroaggregates are disrupted in water. The encrusted fragments remain as microaggregates (Tisdall, 1994).

In cropped soils under plants, macroaggregates are stabilised mainly by roots and VA mycorrhizal hyphae. Saprophytic fungi also stabilise macroaggregates and it has been suggested that ectomycorrhizal hyphae stabilised macroaggregates in several forest soils. In the field and in pot experiments, VA mycorrhizal hyphae have also stabilised sand dune soils (Tisdall, 1991).

Elliot and Coleman (1988) have hypothesised that the process of macroaggregate development is a dynamic one, in which roots and fungal hyphae function primarily in the initial aggregation, and organic binding agents are largely responsible for the stabilisation phase of this process (Miller & Jastrow, 1990). However, Gupta and Germinda (1988) have presented visual evidence suggesting that fungal hyphae may be involved in both an initial aggregative process via mechanical entanglement and binding by labile organic substances, and a second stabilisation process involving attachment to soil particles by cementing agents such as aromatic compounds (Miller & Jastrow, 1990). Chenu (1989) also concluded that the aggregating action of fungi could be divided into mechanical processes, which are responsible for the initial aggregation, and physiochemical processes which stabilise aggregates by cementation.

Roots and hyphae stabilise macroaggregates because they are relatively large and because they can grow in large pores in soil which, in well drained soils, are likely to contain air even during wet weather. Although most hyphae can enter finer pores than can roots or root hairs, fungal hyphae are predominantly found in the outer regions of a macroaggregate (Tisdall & Oades, 1982), where most of the pores are large. This is because fungal hyphae are aerobes, relatively large (2–27 µm diameter) and can grow in drier soils than bacteria. This may limit the size of macroaggregates to several millimetres diameter and may be why macroaggregates from soils under pasture are less angular than those from tilled soils. The surfaces of stable macroaggregates under grass are rougher and more friable than those from tilled soil. Tisdall

(1991) suggests that microaggregates are attached to a loose network of fungal hyphae in a stable macroaggregate which is easily crushed or broken by tillage.

It is believed that stabilization of aggregates by fungi in the field is limited to periods when readily decomposable material has been added to the soil in large amounts leading to a flush of hyphal growth. This may be true of fungal species which most workers have studied. Such species produce characteristic spores, are isolated easily from soil and grow readily on dilution plates. However, fungal hyphae in the field have been shown to be associated with water-stable aggregates of a red brown earth, with little seasonal variation; unstable aggregates contained few hyphae.

Many saprophytic fungi disappear from soil once they have used their substrate, so their stabilisation of aggregates last for a few weeks only. On the other hand, external hyphae of VA mycorrhizal fungi and their stabilisation of aggregates persisted in one soil for at least several months after plants had died, so may be more important stabilisers than saprophytic fungi are (Tisdall, 1991). Because of the temporary nature of roots and hyphae, their abilities to act as stabilising agents should be related to their continued production, their longevity, and the effects of root products on the activities of the soil biotic community (Miller & Jastrow, 1990).

The term 'soil friability' has been defined as the tendency of a mass of unconfined soil in bulk to crumble and break down under applied stress into smaller fragments, aggregates and individual soil particles (Utomo & Dexter, 1981). One of the aims of tillage is to break up the large soil mass into smaller clods or aggregates. It is therefore desirable that the material of the smaller fragments, which originally comprised the larger clods, has a relatively greater strength than that of the larger clods, otherwise the soil mass could break down into individual mineral particles or dust (Utomo & Dexter, 1981).

Ploughing disrupts the soil, making it more friable. It may also influence the amount of nitrogen that is lost by leaching. The natural water content fluctuations are greater in tilled than in non-tilled soil. These fluctuations can cause weakening and breakdown of clods and can increase the amount of small aggregates produced by a subsequent tillage (Dexter, 1988). Soil which has been recently moulded is usually weaker than the undisturbed soil at the same density and water content. This is because the moulding, which is mainly shearing, breaks the bonds between the individual soil particles (Dexter, 1988).

3.5 Seedbed requirements

The attributes that are required of a seedbed to encourage optimal germination, establishment and subsequent crop development are often a compromise depending on the situation encountered in the field. Adequate aeration and water availability are essential to promote rapid germination. Tillage is required which will produce a fine tilth to encourage water absorption through capillary action, but with sufficient air-filled porosity to maintain adequate aeration (Figure 4). The optimal size and packing state of aggregates will depend on the size of the seed, however, fine, firmed aggregates are required to the side and below the seed to encourage water re-distribution, with looser packing above the seed to promote rapid emergence.

Prolonged waterlogging immediately after seeding can be very detrimental to crop health. Past work (Cannell *et al.*, 1980) has shown that for cereals, long term effects occur after nine days of waterlogging, with crop death after fourteen. In wet conditions, it is essential that there is an adequate distribution of coarse aggregates, and hence pores, within the tilth directly below and to the side of the seed to promote free drainage and rapid root development. The main tilth factor governing shoot elongation and emergence is soil strength immediately above the seed. According to Spoor (1984), aggregate size, within reason, is of secondary importance compared to packing state which also influences gas diffusion to depth. For fine aggregates, a loose condition above the seed is desirable, however, if coarser material is present, this provides greater opportunity for unimpeded emergence.

In order to optimise seed drill performance, a smooth surface of fine tilth, free of wheelings and undulations, with minimal surface trash is required prior to seeding. This is of particular importance for precision seeding operations. Some soil-acting herbicides provide greater crop protection when applied to a fine tilth (Spoor, 1984).

The resistance of soil, in a given condition, to deformation is dependent on a combination of the cohesion acting over a given area of shear, and friction, which is strongly affected by the load applied at 90^{o} to the area of shear (Coulomb, 1776). If the water content of a particular soil is increased, then the resistance to shear reduces (Figure 5). It is widely recognised that there are two main categories of soil deformation: brittle and compressive soil failure (Spoor & Godwin, 1979).

Brittle soil deformation is characterised by the development of a few planes of weakness through contact with a tillage implement culminating in an increase in soil bulk volume and a reduction in bulk density (Figure 6). Compressive (plastic) soil deformation occurs under conditions of high confining stress. Loading causes the development of many interacting failure planes resulting in a decrease in soil volume and an increase in bulk density (Figure 7). The resistance of soil to deformation is very dependent on soil type, moisture status, applied load and confining stresses prevalent during loading (Earl, 1997a). Soil under increasing load will always deform where resistance to deformation is at a minimum. To achieve any desired tillage outcome, it is therefore necessary to arrange for that outcome to coincide with minimal resistance by adjusting the loading force and confining stress to encourage appropriate modes of failure to occur (Spoor, 1984).

3.6 Cultivation operations

Any tillage operation can be classified under five broad categories (Spoor, 1984):

- Loosening,
- Clod size reduction,
- Clod sorting,
- Compaction,
- Surface levelling.

Seedbed requirements for promoting optimal crop establishments are very dependent on the soil and climatic conditions likely to limit crop performance in a given situation. There is, therefore, no single ideal tilth condition to suit all situations. Often, risk from a number of limiting factors needs to be considered. However, this can lead to a conflict regarding seedbed attributes and so a compromise is generally necessary.

Earl (1998) presents an overview of the soil, plant and implement considerations for optimising tillage operations.

3.7 Tillage

3.7.1 Impact of conventional tillage

Intensive and often excessive tillage practices result in reduced inputs of crop residue, accelerated decomposition of soil organic matter (SOM) and losses of SOM-rich top soil by wind and water erosion (Arshad *et al.*, 1990). This decline is aggravated if fallow is included in the rotation where the soil is cultivated to ensure no plant growth or where crop residues are removed. Where soil is cultivated frequently, aggregates are exposed repeatedly to physical disruption by rapid wetting and raindrop impact, as well as to shearing by tillage implements. Excessive tillage also pulverises the soil and exposes it to the sun. The net effect is to expose previously inaccessible organic matter to micro-organisms and thus to stimulate oxidation and loss of organic matter. Decreases of 12 to 125 % in organic carbon have been reported under conventional tillage as compared to zero-tillage, depending on soil type (Arshad *et al.*, 1990). This decline in organic matter is also usually accompanied by a decrease in the number of water-stable aggregates. It appears that organic matter plays a major role in binding aggregates to withstand stresses caused by rapid wetting (Tisdall & Oades, 1982).

Tillage practices can alter the vertical distribution and quantity of organic matter in surface soils. Several studies under various soil and climatic conditions have shown an important impact of tillage on SOM content, which has led to the conclusion that the adoption of reduced tillage practices, in particular no-till, will result in an increase in SOM levels and to carbon sequestration in soil (Angers *et al.*, 1995). However, in studies under cool, humid climates in which the whole Ap horizon was considered, differences in total soil organic carbon induced by tillage were not obvious, especially when measurements were based on an equivalent depth to compensate for differences in soil bulk density. It has been suggested that although aggregate disruption induced carbon mineralisation, the overall effect on total carbon loss was insignificant (Angers *et al.*, 1995). This lack of change in SOM appears to be limited to cold climates as other studies have shown a significant impact of tillage on SOM.

It is known that tillage breaks aggregates, disrupting the network of roots and hyphae and exposes organic matter to microbial attack (Tisdall, 1991). Soils that have been in conventional tillage for many years, therefore, often lose a substantial part of their organic matter, including organic aggregating agents. In these soils, rapidly produced binding agents such as extracellular polysaccharides (EPS), may be important aggregate stabilisers in the initial stages of reduced tillage management. Other organic binding agents may take more time to develop (Roberson *et al.*, 1991).

3.7.2 Reduced Tillage/Direct Drilling

Reduced tillage is any management practice that leaves some crop residue on the soil surface and physically disturbs the soil less than conventional tillage practices (Figure 8). It improves the environment by conserving soil moisture through reduced evaporation and better infiltration, and by controlling soil erosion by wind and water (Bailey & Duczek, 1996). It can reduce costs by decreasing fuel consumption. It includes techniques such as direct seeding which places seeds with minimal disturbance in the soil, zero tillage or no-till which leaves all crop residues on the soil surface or minimal tillage which leaves varying amounts of residue on the soil surface (Bailey & Duczek, 1996). Ball *et at.* (1996) found that the surface soil under direct drilling was more stable, less compactable and had greater plasticity limits than under ploughing. However, particle size distributions were unaffected by tillage so that differences in soil properties were attributed to differences in the quantity and quality of organic matter.

Soil water conservation can be enhanced with conservation tillage systems and the amount conserved is directly influenced by the type and amount of crop residues present and the agro-ecological zone. Crop residue decomposition is 1.5 times slower on the surface than when buried (Lafond *et al.*, 1996a).

Grain yield can be improved with conservation tillage and is related directly to the amount of water conserved (Lafond *et al.*, 1996b). In field trials on the Canadian prairies, zero tillage grain yields significantly exceeded those of conventional systems and minimum tillage in 30 to 50% of the site years when growing season precipitation was below normal. This is believed to be related to better soil water conservation and greater water-use efficiency under zero tillage, compared with other tillage systems in years with below normal precipitation and particularly when June and July precipitation was low (McAndrew *et al.*, 1994). Because the increase in stable aggregation under no-till soils is related to the length of root and of vesicular arbuscular (VA) mycorrhizal hyphae and because organic residues accumulate at the surface, most of the improved aggregation is in the top layers of soil (Tisdall & Oades, 1982).

In studies by Arshad *et al.* (1990) on agricultural soils, the C and N contents of the no - till soil were *c* 26% higher than those of the conventionally-tilled soil. The increased contents of SOM resulting from reduced tillage can have mostly positive effects on soil physical conditions, especially on soils naturally low in OM. Organic matter under no-till contained more carbohydrates, amino acids and amino sugars. Glucose was the most abundant monosaccharide and the no-till soil contained significantly more than the conventionally tilled soil (Arshad *et al.*, 1990). Judging from the higher C and N contents and enrichment in biopolymers (carbohydrates, proteins and peptides), the no-till system brings about enhanced biochemical activities. The no-till soil had a slightly higher C-N ratio than the conventionally tilled soil but this was not significant. The pH of no-till soil was significantly lower than the pH of conventionally-tilled soil. Increased amounts of organic C under no-tillage may have contributed, at least partly, to the acidification (Arshad *et al.*, 1990). Thus, from the standpoint of soil fertility, the no-till system not only improves the quality of OM but also increases its quantity (Arshad *et al.*, 1990). Ball *et al.* (1996) found that organic carbon and carbohydrates were concentrated near the surface of direct drilled soil compared with a more uniform distribution with depth in the ploughed soil.

Despite these benefits, reduced vegetative growth of direct drilled wheat has meant that direct drilling has not received more support from farmers in Australia. Suggested causes for reduced growth include reduced availability of nutrients, lower soil temperature, increased soil strength and an increase in pathogenic fungi and root inhibitory bacteria (Kirkegaarde *et al.*, 1995).

As findings vary on the impact of reduced tillage on grain yield, ranging from a reported increase (Lafond *et al.*, 1996a) to a significant decrease (Kirkegaarde *et al.*, 1995), more research is needed into the individual factors affecting crop yield under reduced tillage. When this has been established it will be easier to list necessary criteria when considering the use of reduced tillage. Cannell *et al.* (1979) suggest that drainage, minimising trafficking and early drilling are just as important as texture and depth to an impermeable layer. These criteria have been used to show the distribution of three classes based on the relationship between yields from conventional and reduced tillage rather than suitability (Figure 9). They stress the need for careful and appropriate management techniques to achieve maximum benefits from reduced cultivation.

3.7.3 The impacts of tillage and reduced tillage on soil micro-organisms

A review of the effects of tillage on soil fertility indicates that there are more fungi, actinomycetes, bacteria, facultative anaerobes, and denitrifying microbial populations in zero tilled soils than in ploughed fields (Bailey & Duczek, 1996). Beare *et al.* (1997) also found significantly higher amounts of fungal hyphae in zero tilled soil. The effect of tillage practices on soil microbial populations may be a factor contributing to the measured differences in soil water storage and water use efficiency (Radford *et al.*, 1995). VA mycorrhizal fungi, which increase the uptake of nutrients in plants, produce more spores in the top 8 cm of soil with zero tilled soils (Bailey & Duczek, 1996) but are reduced by cultivation (Gupta & Germinda, 1988). In direct drilled soils, roots may follow old root channels where ineffective propagules of VA mycorrhizal fungi are probably concentrated. Hence the new seasons roots in direct drilled soils could become mycorrhizal and stabilise aggregates more quickly than those in tilled soils (Tisdall, 1991).

3.7.4 The impacts of tillage and reduced tillage on crop diseases

Pathologists recommend deep ploughing to bury and destroy the stubble inoculum, whereas soil management specialists argue that this causes rapid soil degradation. Mehta (1996) found that the commonly used implements do not incorporate adequately the stubble and that reproduction of the pathogen on the unincorporated stubble continues for over two years. Reduced tillage may result in a decrease in some diseases (common root rot) but an increase in others (tan spot and *Septoria* complex) (Bailey & Duczek, 1996) depending on the pathogens method of dispersal and ability to survive in the soil when a host plant is not present.

Tillage practices need to be combined with environmental factors when assessing their impacts on crops. The influence of tillage practice on grain yield was closely related to the effect of tillage on cereal root disease when levels of disease were moderate to high. Where the incidence of root disease was low, grain yield differences due to tillage treatments were generally related to agronomic factors such as seed depth and seedbed condition (Roget *et al.*, 1996).

3.7.5 Future of reduced tillage

Without additional disease control measures, reduced tillage appears to promote unacceptable levels of pathogens. Diseases that were less economically important under higher tillage regimes may become more important under reduced tillage, but location and local environment largely influence which diseases will be present. Crop rotation is a key factor in residue management for disease control (Bailey, 1996). The conservation tillage technologies generated to avoid soil degradation, and the disease management technologies generated to reduce yield losses need to be combined to achieve success in sustainable integrated disease management programs (Bailey & Duczek, 1996; Mehta, 1996). Lafond & Derksen (1996) go so far as to say that zero- tillage represents a starting point in the evolution of sustainability.

It appears that, although reduced tillage is a valuable tool in soil structure conservation, it is not sufficient to simply incorporate it into an existing agricultural system without considering other issues such as plant disease. For reduced tillage to be economically viable, arable farming practices such as cultivation and crop rotation will need to be considered in conjunction with local environmental factors.

4 Systems of soil structure characterisation

4.1 Quantification of soil structure

Methods to standardise soil structural determination have been receiving attention since 1956 and a series of approaches have been assembled (International Society of Soil Science, 1967; Burke *et al.*, 1986) which describe the various methods used in laboratories. The methods include the following:

- Sampling for soil structure measurement
- Inherent soil properties, for example, particle size distribution
- Structural state parameters, for example, bulk density
- Water and air flow parameters, for example, hydraulic conductivity
- Soil strength and stability, for example, structural stability
- Soil morphology, for example, preparation of soil thin sections

There are several laboratory methods (image analysis, sieving and weighing) for measuring aggregate size (International Society of Soil Science, 1967) but these methods are often used to help to understand a specific pedological property or process and results are specific to that particular problem. Consequently, the concept of soil structure can have a different emphasis depending on the observer’s view point. For some it may be the arrangement and number of voids that affect water holding, water flow and gaseous exchange (Nagarajarao & Jayasree, 1994), whereas for others it may be the development and the stability of the aggregate (Baumgarth & Horn, 1993).

4.2 Field description soil structure

In general, the description of soil structure in the field follows a purely observational route with no linkage to the function required by the structure. This is inevitable, as the surveyor requires a generalised set of rules for the description of what he/she sees in the profile. Soil survey techniques tend to consider the highest order of the hierarchy: the macro-structure. Thus the Soil Survey and Land Research Centre (Hodgson, 1997) give descriptions from field observations which refer to the size and conformity of the aggregates without trying to quantify the macro-pore distribution (Table 1, Figure 10). There is still a need to develop an unambiguous description of soil structure, which might best be based on functional descriptions of structure. This implies, for instance, that the description of a structured seedbed may vary depending on the process to be enhanced or the function to be optimised.

In the context of the aims of this project, the field observation, description and quantification of soil structure will carried out by farmers with limited experience of ‘good’ and ‘bad’ structure beyond their own farm environment. Consequently any structural assessment recommended must be simple, rapid and accurate for it to be used confidently in the field by personnel who may not be particularly knowledgeable about identifying ‘good or bad’ structure at the present time. Systems of assessment that rely only on soil collection and laboratory analysis will not fulfil the requirement.

All that is needed to examine the soil in the field for structural problems is a spade, a penknife and a little experience. It is essential to dig holes - nothing can be seen from the surface. As most fields are quite variable several holes in each field will be necessary. Holes need not be large, but should go down to at least 60 cm depth. The soil must be in a moist state for a reasonably accurate assessment.

Generally, only topsoils and possibly the immediate subsoil are considered. This inevitably moves the concept of structure from that in the natural state to where the aggregates have been altered and distorted by cultivation and the use of other machinery. However, the terms developed and used for “natural” structures can still be used.

Several methods have been developed to enable the assessment of soil aggregation in the field by direct observation, with some being more subjective than others. A method to describe the extent and severity of structural breakdown at the soil surface has been developed by Boekel (1965) but is not known to have been evaluated in the UK. Another system of assessment, developed and used by MAFF (MAFF, 1969, 1970a), is based on wetness and soil bearing capacity and relies on the soil physical properties of soil changing with moisture content - from plastic when wet to rigid when dry. These different states are termed ‘consistency’ and assessments of soil consistency aid decisions on cultivations and grazing.

In cultivated topsoils, a system of structural assessment developed by Peerlkamp (1967) has been tested on experimental ley grassland sites (Eagle, 1973). The results show that differences in soil structure can be distinguished between leys of different age. Further tests in advisory work have also given useful results (Trafford & Davies, 1971) and show that variation between operators is not great and the order of differences between different soils similar (Batey, 1973). The Peerlkamp system involves visual examination of a spade full of soil from about ten different points in a field. These are laid on the ground and gently broken apart by hand. A variation in the method drops the soil from waist height to provide a more objective break up of the soil. An ‘ST’ number is given to the soil (Table 2) based on a consideration of the following:

- Aggregate development
- Cohesion of soil particles
- Aggregate porosity
- Root development

The assumption is that medium or finer crumb structure, low cohesion, good porosity and absence of surface capping provide a good medium for root development.

5 Construct a risk assessment matrix

5.1 Effects of structure on soil processes

Soil structure can be expected to have a significant effect on soil processes: in particular hydraulic and aeration processes, both vital to plant growth, will be affected. Table 3 summarises how some process parameters might be affected by soil macro-structure, apart from water retention, which is affected by both macro- and micro-structure. In general however this non-quantitative approach is only useful for ranking structure and because statements about the effects of structure can be made in terms used by the soil surveyor.

Clearly there are a number of factors which predispose a soil to good structural condition or a poor one. The relative importance of each has not been well quantified and, to a certain extent, the definition of 'good structure' depends on the process which is to be optimised. For instance, air movement, water movement, water retention, germination and soil bearing strength may all need particular, but differing, structural conditions.

5.2 The concept and assessment of soil structural stability/instability

Structure stability can be defined as the resistance of the soil structure to external factors such as water. Soils that naturally have a good structure in the long-term have a 'stable' soil structure; those that would naturally lose all aggregation have an 'unstable' structure. Thomasson (1984) proposed a classification of soils according to their topsoil stability/instability in relation to slaking (Table 4).

Instability in soil structure leads to small macroporosity which in turn leads to poor infiltration, capping, anaerobic conditions or excessive soil strength on drying. Thomasson suggests an increase in stability for calcareous and iron-rich soils and a decrease for sodium-rich soils and areas where excess winter rainfall (Jones and Thomasson, 1985) is more than 250 mm or the field capacity period more than 150 days.

5.3 The assessment of structure regeneration

Thomasson (1984) proposed a classification of UK arable and improved grassland topsoils according to their 'structural regeneration' (Table 5). It applies to soils that have suffered compaction damage by implements or livestock and can be defined as the tendency of a soil to revert *naturally* to a porosity, density and strength state similar to that prior to compaction.

Soil compaction (figures 11 & 12) results from complex interactions between soils, machinery (load, type and dimension of pneumatic tyres, inflation pressure, vehicle speed, wheel slip, number of passes), crops, weather conditions and field history. The recovery of a compacted soil is greatly influenced by swelling and shrinkage in soils with sufficient clay contents and by frost action (Soane *et al.*, 1982). In areas where soil freezing in winter is only slight or absent, the effects of wheeled traffic are likely to persist for several years. In the UK, Pollard & Elliot (1978) have shown that compacted zones in a controlled traffic experiment on a sandy loam soil persisted for at least two years in the absence of any further traffic. Soil compaction can affect both the topsoil and the soil that lies below the depth of primary cultivation. It can lead to the following crop responses:

- Poor germination: waterlogging in the topsoil depresses the soil temperature and excludes air, encourages the production of gases which are toxic to plants.
- Poor response to fertilisers: root development and crop growth, restricted by imperfect structure lessens the response to fertilisers. Waterlogging also causes fertiliser nitrogen to be changed into gases which are lost to the air.
- Traffic damage: damaged structure increases the risk of wheel slip and rutting so accelerating further damage.
- Crop diseases and pests: Plants weakened by waterlogging are less resistant to disease and pest attack.
- Droughtiness: shallow rooting plants cannot obtain sufficient moisture and rapidly show drought symptoms.

6 Validate the vulnerability classes and risk assessment matrix

The following assessments of structural vulnerability have been investigated:

- Aggregate and bulk strength indices (section 6.1)
- Biophysical vulnerability (section 6.2)
- Peerlkamp Index (section 4.2)
- Structural stability (section 5.2)
- Structural regeneration (section 5.3)
- Structure Quality Index (section 6.3).

It proved difficult to construct a robust vulnerability matrix as originally planned, although several attempts were made. The main reason being the complex interactions between the measured and observed parameters and the over-riding influence of timeliness and machinery inputs.

The investigations made to determine ergosterol levels and the aggregate and bulk strength indices are outlined below. More details of the methodologies and the theories behind them are to be found in MacGovern (2000), Harding (2000) and White (2000).

6.1 Determining soil structure vulnerability from soil strength measurements

Many authors (< biblio >) have highlighted the importance of scale in the description of soil structure. Many models developed to describe soil structure are based on hierarchy (Dexter, 1988). The lowest hierarchical order is that of single minerals. The next hierarchical order is the larger compounds resulting from the combination of the lowest order and so on. Another approach to describe the range of sizes present in soil is to use fractals to describe soil particle sizes. This implies that the particle size distribution reflects a micro-structural distribution within a macro-particle. This approach has been shown to have some drawbacks (Addiscott & Dexter, 1994).

In the work described in this section, soil structure is taken to be the large-scale macro-structural arrangements of aggregates and peds within the soil profile. In particular, emphasis is placed on the structure in a tilled seedbed which is also referred to as soil tilth. A “good” structure in this sense means a well-aggregated soil with separated aggregates with large macro-pores separating the structural units. Such a structure would be characterised as having good aeration and good infiltration and drainage properties (Figure 14). A collapsed structure is taken to mean the situation where the aggregates have collapsed, the material of the aggregates having filled the macropores. Poor aeration and lowered infiltration and drainage properties would characterise a collapsed structure such as this.

While soil particle size distribution usually changes only slowly with time, structure may change over very short periods of time (Figure 14). Mechanical disturbance of the soil imposing a stress system on it, is usually a prerequisite for structure collapse. The stress may arise by natural forces of wetting and drying, freezing and thawing, biological activity or by mechanical intervention such as tillage and cultivations. The ability of soil aggregates to resist breakdown is a function of the internal soil particle bonding within the aggregate. Breakdown and separation of individual soil particles requires that a force is applied to the soil in such a way as to break the bond. The strength of the bond being broken depends on the nature and size distribution of soil particles, their surface chemistry and their packing arrangement.

Methods to measure bulk shear strength usually attempt to quantify the cohesion and the angle of internal shearing resistance either by direct shear or by triaxial tests. However these later can only be used in a laboratory and are therefore of limited use for structured soils. The principal direct shear devices that have been used to measure shear strength of agricultural soils include grouser plates, translational shear boxes (Figure 15), NIAE torsional shear boxes, sheargraphs and annular torsional shear equipment. Bulk soil strength has often been related to water content. At very low or high water contents, soil strength has been shown to change abruptly but a clear regression has been fitted for some water contents (Mielke *et al*., 1994). The maximum shear strength of a soil decreases as the moisture content increases and could be due to the higher pore water pressure with higher moisture content thus reducing the effective stress. Other soil properties also influence soil strength. The higher the bulk density, the higher is the shear strength. As organic matter increases it has been shown to decrease bulk strength because the porosity increases. However if the porosity remains the same then an increase in organic matter increases tensile strength (Ohu *et al*., 1985).

Aggregate strength is very often measured by the crushing method (Dexter *et al*., 1984, Guérif, 1988, Hadas & Connard, 1988). These experiments have shown correlation’s between aggregate strength and porosity, clay content and organic matter. One of the drawbacks of this method is that the aggregates must be in the friable water range (Guérif, 1988). Water content has a strong effect on soil strength, not only directly, but also indirectly by affecting the bonds between particles created by exchangeable cations, clay minerals, organic matter and water suction (Dexter, 1988). Baumgartl & Horn (1991) developed a technique to measure the shear strength of individual aggregates that would allow them to be compared directly to bulk shear strength.

In tilled soils, where aggregates may be loosely packed after seedbed preparation, the bulk soil is likely to have low strength in shear because there is little bonding between aggregates. As soil structure collapses, the strength of the bulk soil is expected to increase as soil in-fills the macro-pores creating a more compact and rigid soil profile. Aggregates that can be extracted from the soil profile are expected to fail at a higher stress than the freshly tilled bulk soil. The aggregates are assumed to remain within the collapsed profile. Fig. 13 shows the expected differences in bulk shear between a loose, freshly tilled seedbed and a collapsed seedbed.

We hypothesise that, as shown in Figure 13a, the failure plane is predominantly through the macropore region with little aggregate shear. In this case, aggregates would be expected to move along the line of shear as the bulk soil dilates. In Figure 13b the structure has collapsed and the failure plane passes through the aggregates. In this situation the bulk strength of the soil is similar to the aggregate strength. From the above arguments we propose that differences between independent measurements of bulk strength and aggregate strength give an indication of the differences between well-structured and collapsed soil.

6.1.1 Preliminary results

The field bulk shear plate apparatus consisted of a rectangular plate with short, vertical spraggs (Figure 16). The plate was inserted into the soil and winched sideways to induce lateral shear. A tension link recorded the force at failure of the soil, which was taken as the maximum force recorded. The process was repeated at different normal loadings (Figure 17). The data show that in all cases the bulk shear stress at failure was lower than the aggregate strength as suggested by the earlier discussion. The shear stress at failure for the sandy loam soil was significantly smaller ($p < 0.05$) than that for the clay soil for both the aggregates and bulk soil. This was expected, as cohesion is always likely to be greater where there is a high clay content.

Two differing soils were sampled on six occasions between February and April 1999. Soil water content varied at each field visit. Figure 18 shows shear stress data as a function of the water content of the soil. Analysis shows that there is a significant correlation between the aggregate shear strength and the water content of the soil at shear. However, no significant correlation between bulk strength and water content could be found for either soil. It is to be expected that water content plays an important role in determining soil strength, but it is interesting to note that the predominant effect here is in the internal bonding of the micropore region and not in the inter-aggregate region of the macropores.

In order to provide a standard relationship for any soil between bulk strength and aggregate strength a normalised index, I, was defined as follows:

$$I = \frac{t_{agg} - t_{bulk}}{t_{agg} + t_{bulk}}$$

where t refers to stress and the subscripts *agg* and *bulk* refer to the aggregates and bulk soil respectively.

The value of the index can take values from 0 to 1. A value of 1 indicates a very weak bulk soil, but containing strong aggregates. This situation might arise where the soil has a good tilth and the aggregates are dry. There is little shear between the aggregates, but the dry aggregates are relatively very strong. A value of 0 occurs where the aggregate strength is similar to the bulk strength as would be the case where the aggregates have coalesced. Such a situation arises when the soil structure has collapsed. The nature of the index is therefore one which can indicate structure condition in the soil.

The application of the index to the two Silsoe soil types is shown in Table 6. It is noticeable that the values are all less than one as expected. The highest values occur in the clay loam soil and some very low values occur in the sandy loam soil. Analysis of variance shows that the difference between the means of the indices for the two soils is significant ($p < 0.05$) with the mean for the clay soil being greater than that for the sandy loam soil. However, no significant differences were found between the autumn loosened and unloosened soil.

The data imply that the structure created at tillage in the autumn has naturally declined due to weathering effects. However, the time sequence of data shows that the sandy loam soil had little recovery of index over the measurement period while the clay soil does appear to recover structural coherence, presumably due to swelling and shrinking as the soil wets and dries.

6.1.2 Modified equipment

A simplified bulk shear measurement device based on torsional shear was designed and constructed (Figure 19). The criteria for the device were that it should be light-weight, not impose a vertical load on the soil under shear and be large enough to measure a representative volume of soil. The diameter of the device was 400 mm and seven vertical blades were arranged vertically from 100 mm radius to 200 mm. Sheared soil was able to rise in front of the blades with no restrictions. Measurement of the torque at failure was recorded and the measurement converted to a failure stress by a strain-gauged cantilever arm.

Aggregate shear was measured by collecting aggregates from the field at the same time as the bulk shear was measured and taking them to the laboratory. These aggregates were thus at a similar moisture condition to those in the field. The aggregates were mounted in a modified translational shear apparatus and subjected to lateral unloaded shear (Figure 15). The peak shear force was recorded and the dimensions of the orthoganol axis of the shear plane of the aggregate were measured. The cohesion of the soil within the aggregate was determined from these measurements

The bulk density of the soil in the field was recorded using the ball replacement technique. In this way both field bulk density and water content were determined. Aggregate density was found by wax coating the aggregates and determining their volume and so their density.

Eighteen sites were identified as representative of the range of soils under arable farming in the England. The soil textures at these sites ranged from loamy sand to heavy clay and were separated by geographically so they occurred in differing agro-climatic areas (Table 7). The sites were each visited twice. The first visit was between October and November 1999 and the second visit was in February 2000. All the sites were autumn cultivated and seedbeds prepared and sown just prior to the first period of sampling.

6.1.3 Results from field and laboratory measurements

The basic data derived from the field and from laboratory analysis are presented in Tables 8a & 8b. The strength of the bulk soil was similar to the values found in the earlier experiments on the same soils. In all but one case, the strength of the soil in the winter case was stronger than that in the autumn case. Also, in all cases, the bulk density of the soil was found to increase from autumn to winter. Both of these results are consistent with a partial collapse of soil structure between autumn and winter as the soil gets wetter. Aggregate strength decreased between autumn and winter in all but one case where only a small increase was noted. This is probably due to the change in water content that was higher in all cases in winter. The calculated strength index was positive with some high values in all cases except the sandy loam soil of Avenue field which was very low. This is consistent with soils in a loose state following seedbed preparation. The high values of the autumn are in contrast to the significantly lower ($p < 0.05$) values of the winter where generally values were found to be typically half that of the autumn. Indeed, some negative index values were found where bulk strength was found to be greater than aggregate strength. It was not expected that the aggregates should have less strength than the bulk soil and the winter 1999 investigations did not produce any negative index values. This apparent anomaly may be due to the measurement technique, sampling errors or due to the structure collapse mechanism.

The measurement technique for the aggregate strength is thought to be satisfactory and did not differ in principle from the initial investigations and the field survey. However, the bulk shear measurement is different, in that it produces torsional shear in which lateral shear is induced at 100 mm depth and soil is allowed to loosen in front of each blade. This is in contrast to the equipment used in 1999 which surcharged the soil and in which no bulldozer effect was allowed. The assumptions made in developing the equation for the torsional shear apparatus may overestimate the shear stress at failure in a compact soil. Sampling errors may also be responsible for high bulk strength measurement compared to the aggregate strength. Five replicate measurements were made in the field at each location and variability between measurements was noted. Aggregates were taken from the disturbed soil within the torsional ring.

The soil in collapsed soils presented little evidence of structure. The collapse mechanism is one of aggregate erosion with eroded particles infilling the large voids between the aggregates. This infilling material then sets within the macro-pores and locks the structure. Cementing by small particles and in some cases by calcium slats may result in a strong bulk soil. Aggregates removed in such situations may have lower strength leading to a negative structural index.

In order to investigate any possible relationships between the strength parameters and other soil properties, a correlation matrix (assuming linear correlations) was constructed. The resulting correlation matrix is shown in Table 9. In general the strength of the soil increased as the clay content increased although no significant linear relationship was found between bulk shear stress at failure and clay content was found. The aggregate shear at the winter visit was found to be significantly related to the clay content ($r^2 = 0.64$; $p < 0.05$).

No significant relationships were found between the strength parameters and organic carbon.

6.1.4 Conclusions relating to structure vulnerability using soil strength measurements

The data for soil strength derived in the field was used to test the hypothesis that differences between bulk shear strength and aggregate shear strength provide a descriptor of the structural state of the soil. The initial field results were promising in that significantly different values of the derived strength index based on measurements of bulk and aggregate strength were found for two distinct soil types under arable agriculture. The index for the clay soil that has recognisable macro-structure in the late winter was, on average, twice that for the sandy loam soil that is prone to structure collapse under natural weathering conditions.

Further field trials on 18 different soils in differing locations challenge the simple conclusion that the strength index provides a robust quantification of structure state. Clay content of the soil is found to be the most dominant influence on the strength index. This is not surprising as the strength measurements provide an estimate of the apparent cohesion of the soil.

The poor relationship between organic carbon content of the soils and strength measurements was unexpected as organic matter is often cited as a precursor to good structure development. This finding confirms, however, the conclusions of Loveland *et al.* (2000). However, the related weak agreement between the derived strength indices and the observed structure in the field may indicate that while the strength measurements here do provide a measure of structure collapse they do not assess the same structural issues that visual inspection addresses. The changes in the bulk strength were generally much less than those for the aggregates in the 1999 winter studies over three months on the same soil, and this was true - but to a lesser extent - for the 18 soils in the 1999 - 2000 study comparing autumn and winter values.

6.2 Biophysical vulnerability of soil

Ergosterol, a phospholipid only found in live fungi, was chosen as an indicator of biological health. The rationale to choose fungi over any other microbial community was firstly, the ease, reproducibility and accuracy of the measurement when confined to one soil type; secondly, the fact that tillage has been shown to have the largest immediate effect on fungal populations. A summary of the main measurements and their relationship with specific processes is given in Table 10.

The main field site was at the Scottish Agricultural College, Peniciuk, Edinburgh. Figure 20 summarises the layout of the site and the main soil management variables examined. A key feature was that soil, initially under a long-term grass management regime, has been simultaneously turned over to a range of management regimes, within an area that is sufficiently small that all other factors may be assumed constant across the site. The imposed regimes vary in the degree of disturbance from zero (grassland) through limited (direct drilled) to substantial (conventional tillage). Thus, the contribution of the land management systems to the resilience of the system under a range of imposed external stresses may be examined. Figure 21 illustrates a typical distribution of ergosterol in various land management regimes and nitrogen levels. Over the two growing seasons when ergosterol concentrations were measured a number of key facts became apparent.

Levels of viable fungi in the management regimes were ranked consistently as *Grass = Direct Drilled >> Ploughed*. It appears that the initial effect of conventional ploughing was to tear the fungal mycelia apart and quickly reduce the overall viable fungi in soil. Over the two growing seasons it was clear that, at no stage, did the levels of fungi in the ploughed soil catch up with the other soils. The conclusion to be drawn from this set of results is that not only does the action of ploughing enforce a rapid decrease in fungal biomass, it also creates a different habitat for the fungi that limits the extension of the fungal community, in each soil system. In short, the legacy of the ploughing, at the scale of the fungal population, remains throughout the growing season.

Additionally, during the growing season, we observed a massive and immediate decrease in fungal populations after the application of a surface fungicide. This was to be expected. However, rather unexpectedly, one month after the application, fungal biomass was back to its original levels in all sites. We do not know the composition of the fungal community. However, we can assume that the fungicide acted on the pathogenic fungi for a reasonable time period (there was no obvious fungal attack at least on the leaves). The non-pathogenic, or at least the non-targeted fungal community, responded to reach their maximum levels within the habitat provided by each soil, within a relatively short time scale, leaving the total fungal biomass unchanged. The full dataset (i.e. over two growing seasons) is still being analysed. However, the one constant in all data over all months, is that the grassland and direct drilled plots have a similar fungal biomass and the ploughed soil has a significantly lower fungal biomass.

6.2.1 Microbially-derived organic matter

An analysis of the light- and heavy-fraction organic matter (from N0 plots) was carried out. The latter has been ascribed to plant-derived carbohydrates, and the former to microbially-derived carbohydrates. This technique has been used to provide an indication of microbial activity in relation to the stability of the soil system (Figure 21). Mirroring the ergosterol results, it was observed that that the light fraction was significantly greater in the grassland soil, compared to any other treatment. No other comparisons were significantly different.

6.2.2 Basic soil measures

To ensure a reasonable set of baseline data, a range of traditional measurements was carried out during the second growing season: namely, total organic matter, particle size distribution (clay loam) and pH. Whilst some significant differences were observed, the overall differences were small and analytically not significant.

6.2.3 Measures of structural resilience and stability

A new approach was developed to test for the structural resilience of soil after external stresses have been added. Essentially, making the soil into a paste, pouring that paste into a flat container, and drying the soil in an oven at 40^{o}C destroyed all observable structure. Image analysis was then employed to measure various attributes of the regenerated cracks.

Resilience

Examples from each soil are given in Figure 23. The lengths and area of cracks were calculated, along with the number of peds generated. The main differences were found between the ploughed soil when compared against either the direct drilled or the grassland: the greatest number of peds and the lowest crack area was observed for the ploughed soil. The latter is an indication of the lack of structural regeneration in the ploughed soil, showing that continued high inputs of disturbance decrease the soil's ability to reset itself, in terms of soil structural attributes. This correlates well with the ergosterol data.

Interestingly, during the development of the technique we noticed that the initial protocol of saturating the soil prior to slurrying lead to, as observed by eye, quite different consistencies of soil slurries, especially between the ploughed soil and the grassland soil. We investigated this further by measuring the Liquid Limits of the soils using the standard Drop Cone Penetrometer method. The results proved interesting, and unexpected. Whilst the Liquid Limit of the grassland and the direct drilled soils were the same (52%), the Liquid Limit of the ploughed soil was significantly lower (40%). As the Liquid Limit has been used to aid in the prediction of the available soil work days, this again leads us to believe that there is operational significance to most of the differences were are picking up. Due to these results, all the regeneration data is expressed from soil that was initially wet up to its Liquid Limit.

Shrink-swell properties

The ability of a soil to shrink and swell during cycles of wetting and drying, or freezing and thawing, is crucial to the soil's ability to regenerate structure. A technique was devised to analyse, in real time, the swelling properties of soil, under controlled soil matric potentials and simultaneously monitor the rate of water uptake. It should be noted that this part of the project was not part of the MAFF-funded project, but has important implications for the work. Whilst results are still been analysed, some important conclusions can be drawn. Preliminary data suggests that are significant differences between the shrink-swell properties of the ploughed and the grassland soils at Beechgrove, but no obvious differences in their ability to take up water.

Stability

An X-ray sedigraph was used to examine the aggregation properties of soil from the three soil management sites. It is important to note that the results are based on undispersed samples. The results, using a statistical technique that compares distributions of undispersed aggregates, showed that the ploughed soil and grassland soil exhibited statistically significant ($p < 0.05$) distributions of aggregations. This is an interesting result, as the traditional method of particle size distribution did not show any significant effect. Rather, the latter method was able to recognise that the fundamental units of the soil (sand, silt and clay) were exactly the same. The X-ray methodology was able to show that the imposition of different management practices significantly affected the operational properties of the soil. Additional, traditional, water dispersible clay measurements from all soils were inconclusive and showed no obvious trend between sites.

Strength measurements

The strength of a random selection of the individual peds generated during the desiccation process in the resilience technique were investigated to provide an indication of the effect of applying an external load (analogous to the effect of a plough breaking the soil profile apart) (Figure 23). The results show that as the degree of disturbance increases (i.e. from grassland through to ploughed soil) the strength of the individual peds similarly increases. These results relate to soil that was initially slurried at the respective Liquid Limits. As more moisture was added prior to slurrying, the strength of all soils from all sites decreased.

6.2.4 Conclusions from the Beechgrove work

The initial samples were taken about three years after the permanent grassland was partially changed into direct drilling or ploughed. In general terms the overall effect of nitrogen levels in the treatments were low, presumably because there was still a large legacy of the nitrogen from the grassland in all sites. However, the effect of physically disturbing the profile was profound, both for the viewpoint of the physical and biological processes and characteristics of the soil. The greater the degree of disturbance (taking grassland as zero disturbance, direct drilled as limited and conventional ploughing as high), the lower the microbial activity. This impacts directly onto the physical resilience and stability of the soil.

6.2.5 Biophysical assessment of validation sites

Ergosterol levels were measured in the soils at Silsoe used to validate the soil strength methodology (section 6.1.1). There was more ergosterol in the sandy loam sites as opposed to those in clay (Figure 24). The pattern between cultivation treatments was consistent with:
ploughed and loosened < not ploughed or loosened < not ploughed but loosened < ploughed but not loosened.
In terms of disturbance:
not ploughed or loosened < not ploughed but loosened < ploughed but not loosened< ploughed and loosened.
Thus degree of soil disturbance is not directly related to ergosterol levels.

There was no significant correlation between the amounts of ergosterol in the 18 topsoils at the validation sites (section 6.1.2.) (Figure 25) and the other parameters and indices (Table 9a). Five of the sites were sampled in April 1999 and again in autumn 1999. Comparison of the results (Figure 26) showed higher levels in spring as opposed to autumn. All sites had been ploughed and the difference between the levels is suggested as an indication of relative soil health.

6.3 Field descriptions of soil structure

6.3.1 Archive field description

Field assessments of topsoil structure from detailed profile descriptions held in LandIS and the SSLRC paper archive were compiled in a spreadsheet. The size and development of the peds were tabulated against measured data to investigate whether such one-off descriptions can act as pointers to the stability, regenerative ability and vulnerability of topsoils. Organic carbon, sand, silt and clay, water release data, land use and a field description of the structure (size, degree of development and shape) were recorded for each of the 400 profiles included. The profiles were then divided according to land use, but it should be noted that the land use is that at the time of description. The archive includes no reference to the land use in the proceeding months or years, which is likely to be an important influence on the conditions described by the surveyor.

Figures 27 and 28 shows the relationship between organic carbon and the structure size and development for topsoils under arable cultivation, ley and permanent grass. In arable and ley grass soils those with strongly developed, i.e. most obvious structure, have the highest carbon content. At permanent grass sites there is no increase in carbon as the structure develops, whereas under cultivation there is an increase from weak to strong. There is a decrease in the amount of carbon as the size of the structure units increases, regardless of land use.

Size of structural units shows no discrimination in organic carbon at the cultivated sites but there is a decrease from small to very large at the permanent grassland sites, with the highest carbon values being found in small strongly developed peds and the lowest in very large weakly developed peds.

The relationship between described structural development and water holding capacity was also investigated for the arable sites (Figure 29). Total pore space and retained water capacity show an increase as structure improves and a decrease as the size of unit increases. They also show relationships with the Regeneration and Stability Indices with an increase as the stability and rate of regeneration increase (Figure 30).

The adsorption of organic matter to clay and silt is important in determining the stability of organic matter in soils. Hassink (1997) attempts to quantify the amount that can be preserved in different soils on the hypothesis that this is limited. He suggests that there is an important role for carbon occurring at less than 20µm: it being better protected against decomposition and calls this 'stable' carbon. He derives an equation which relates the particle size of fractions less than 20µm to the 'stable' carbon.

$$\text{Stable carbon (g/kg)} = 4.09+0.37(\%<20\mu\text{m})$$

The profiles in the LandIS database do not have the silt fraction divided at 20µm and therefore to facilitate investigation, the assumption was made that 30% of the silt measured between 2 and 60µm was less than 20µm. The amount of this stable carbon was subtracted from the total carbon and a residual figure derived. This is the carbon in the profile that, according to Hassink, is in surplus. If his hypothesis is correct, then negative figures are those sites where the carbon has been "over-exploited" and where the soil, and therefore structure, is unstable. Many topsoils under arable cultivation with very weak structure development fall into this category, together with topsoils with very coarse structure units under arable and ley grass. The largest residual amounts of carbon are found in very well developed structures with small peds, regardless of land use, and are deemed by Hassink to be the most stable (Figure 31).

These findings would suggest advising farmers to aim for the production of a well developed structure with small peds and to maintain and/or improve their levels of organic matter. It then can be applied in reverse to show that on average some soils are closer to a stable equilibrium than others. The average topsoil carbon, silt and clay for soils under arable cultivation from the SEISMIC database (Hallett *et al.*, 1996) were used to calculate the stable carbon across England and Wales (Figure 32). This map should be compared with a similar one produced by Loveland et al. (2000) (Figure 33) using the RothC model of carbon sequestration. The maps are similar in that they suggest that areas in East Anglia, Lincolnshire and the Welsh Marches are "less stable" than elsewhere.

6.3.2 Structure Quality

Hall *et al*. (1977) developed a classification for air capacity and available water which allows assessments to be made of structural quality (Figure 34). The two axes can be considered as aspects of soil structure. Intra-pedal pores appear as available water; pores between peds or between coarse particles as air capacity. Droughty soils have less than 10% available water. On the air capacity axis, a soil is likely to be anaerobic at field capacity and rather impenetrable to rainfall if air capacity is less than 5%. Above 10% both aeration and permeability should be satisfactory. The assumption was made that little additional benefit is obtained from air capacity greater than 15% or available water greater than 20% in topsoils. The sum of available water and air capacity is called "storage pore space" (Hodgson, 1997); it is negatively correlated with packing density (Hodgson, 1997). At higher packing densities excessive soil strength and resistance to roots and implements may impose an additional limitation over and above the simple porosity properties. The extent of this limitation will vary for different particle-size classes, as well as seasonally with water content. However, it is considered that when storage capacity is less than 23% the structural quality be considered as "poor" irrespective of the individual values of air and water. Hall *et al.* concluded that no particle size class is always "good" or "poor" mainly due to differences in bulk density and organic carbon and land use.

6.4 Validation of indices

The structure at the 18 validation sites (see sections 6.1.2 and 6.2.5) was described both in terms of the size and development and also the Peerlkamp index (Table 7).

The correlations between the six indices of structural vulnerability were calculated (Table 9a) and the most significant are summarised in Table 9b.

The more traditional methods of estimating the physical aspects of the soil showed little correlation with the biophysical properties, which brings into question the value of using such data in elucidating the mechanisms behind soil biophysical vulnerability or to predict events where the soil may be vulnerable in the future. However, this does not invalidate their use when considering aggregate and bulk strength where there are good statistical relationships. The Peerlkamp Index is shown to be a very valuable field assessment of structural development having a correlation with strength measurements as well as air capacity. The structural quality index is a useful measure of the success in creating a good seed bed if there is access to measurements, rather than assessments, of air capacity and available water capacity. The assessments as shown in Figure 38 give the potential for achieving a good seed bed in a given soil type. The Stability and Regeneration

Indices then show how vulnerable to degradation is the "potential" structure and the length of time it will take to return to the optimum following damage. It is evident from the validation sites that the actual Structure Quality Index in autumn was better at 8of the 18 sites and worse at 5, whereas five months later the index was better at only 1 site and was worse at 7 sites. This is a reflection of the decrease in Strength Index discussed above. Autumn structural quality was better than winter at 9 sites and worse at 4.

The use of statistical packages to plot the relationships between the measured parameters and the indices (Figure 35) is a help in identifying what is happening at individual sites when investigating the effect of site specific activities, such as whether the site is in conventional or minimal cultivation.

7 Develop a system for farm specific advice on soil structure management

The digitised version of the National Soil Map at 1 km resolution is used as a basis for the presentation of the spatial distribution of the some of the indices considered by the project (Figures 36 to 39). However the use of such maps is limited when identifying actual site conditions on a field-by-field basis. The maps are best considered as a first review of the data to give the user, in this case the farmer or his advisors, an overview of the soils and their vulnerability. The farmer should then assess the properties of the soil by using brochure produced as part of this project.

Alternatively, a field-by-field assessment of structural vulnerability can be made using available 1:25,000 or 1:10,000 scale soil maps combined with estimating the Peerlkamp Index within the fields and digging holes to check for plough or sub soil compaction. The implications of ignoring structural deterioration and/or compaction are seen not just in decreases in yield but also in gross margins (Figure 40).

8 Conclusions

Seedbed requirements for promoting optimal crop establishments are very dependent on the soil and climatic conditions likely to limit crop performance in a given situation. There is, therefore, no single ideal tilth condition to suit all situations. Often, risk from a number of limiting factors needs to be considered, however, this leads to a conflict regarding seedbed attributes and so a compromise is generally necessary.

To achieve a desired tilth condition is fraught with difficulties, as the outcome of any tillage operation is strongly dependent on prevailing soil conditions. However, the application of basic principles of soil-implement interactions will increase the likelihood of accomplishing tillage objectives.

The strength measurement techniques provide some important insights into the behaviour of the soils following cultivation under natural weathering conditions. If structure is to collapse in these situations then it can only be resisted by the internal bonding within the aggregate. However what the studies reported here show is that the process of aggregate breakdown is clearly a complex one that is not described completely by simple lateral shear. They do show that the equipment and methodology innovated as part of this project produce valuable data on the relative strengths of soils and consequently the amount of effort required to move soils. It is a technique that has implications and use not just in agriculture but in land restoration schemes.

The greater the degree of disturbance (taking grassland as zero disturbance, direct drilled as limited, and conventional ploughing as high), the lower the microbial activity, and this impacts directly onto the physical resilience and stability of the soil. The new approaches developed both with funding through this project and in other, closely related, projects offer better guidance to the interactions of the biological and physical approaches in soils.

If soil management advice is to be targeted, then the areas identified with more unstable topsoils and slowest recovery (Figure 40) should be the primary targets for advice and further research as to the relation between carbon levels and structural stability, in particular the fraction of the carbon that is the cause of instability. The common factor between all the approaches is particle size distribution: a proportion of the silt fraction in Hassink (1997) approach and clay in soil strength as reported here and in Loveland *et al*. (2000).

One of the primary objectives of this project is that farmers are provided with farm-specific guidance about soil structural management. Consequently any structural assessment recommended must be simple, rapid and accurate for it to be used confidently in the field by personnel who may not be particularly knowledgeable about identifying 'good or bad' structure at the present time. Systems of assessment that rely on soil collection and laboratory analysis will not fulfil this requirement. Use of the more ‘hands - on method’ such as the “Peerlkamp Index” together with the guidance on structural development and aggregate shape and size contained in new brochure can be used to address the need for a simple and rapid method.

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