Soil Damage by Intensive Arable Cultivation: Temporary or Permanent? [and Discussion]

D. J. Greenland and H. C. Pereira

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Soil damage by intensive arable cultivation: temporary or permanent?

By D. J. Greenland

Department of Soil Science,
University of Reading, Reading, Berks.

Intensive arable production normally involves an increasing frequency of cultivation, and hence an increasing probability of soil compaction, particularly if the soil is cultivated when it is wet. The effects on the potential ability of the soil to produce crops is uncertain, because the relations between soil physical conditions and crop growth are poorly understood. To measure damage requires improved techniques for measuring pore size distribution, as well as pore continuity and stability. Most damage takes the form of a reduction in the number of transmission pores (those greater than 0.05 mm, equivalent cylindrical diameter) although storage pores may also be lost in intensively cultivated soils. Where damage is primarily in the surface soil it can usually be repaired by appropriate cultivations. Where compaction of subsurface soil occurs, or blockage of subsurface pores by dispersion of clay from disrupted aggregates, the damage is less easily repaired. Soils differ considerably in their ability to withstand intensive cultivation. The behaviour of soil aggregates on immersion in water provides a useful guide to those likely to suffer more permanent damage, and those where increasingly intensive production can be safely practised.

Introduction

This meeting is concerned with increases in agricultural yield. A major factor in increasing crop yields is to ensure that optimum soil conditions exist for crop growth. Our understanding of the nutritional requirements of different crop plants is now quite sophisticated, and provision of conditions in the soil where nutrients are not limiting yield is usually possible. Our ability to provide physical conditions in the soil so that maximum production is obtained is much less advanced. There are still gross deficiencies in our understanding of the relationship between soil physical conditions and crop growth. This can be attributed in large part to the fact that we still have difficulties in producing an adequate quantitative description of the physical environment of the soil. While we are unable to describe physical conditions precisely, it is not surprising that we are unable to evaluate their effects on crop growth and develop methods for establishing optimum physical conditions.

It was thought for many years that loosening and opening the soil by ploughing was important to establish appropriate physical conditions. In fact some 40 years ago Russell & Keen (1937) showed that for many soils tillage was important for destroying weeds rather than modifying soil porosity. Nevertheless, devotion to producing a tilth by repeated cultivations has persisted. Little advance has been made in methods of cultivation since the plough was invented in neolithic times. The changes that have occurred have mostly produced larger, multiple pronged implements, requiring greater power to pull, with little critical attention given to determining whether larger implements would in fact do a better job of improving soil conditions for crop growth.

A most important change has, however, occurred in the past two decades. The availability of both pre- and post-emergence herbicides has made weed control without tillage possible, and ‘no-till’ farming methods have evolved, the first real step forward in land preparation for crop production in about 3000 years. This means that we can now think a lot more positively about what is needed in terms of ensuring that the soil is in the most suitable physical condition for maximum crop production, and if tillage is necessary it is conducted for this purpose. This involves mainly determining whether the pore spaces in the soil are adequate to allow sufficient air and water movement and root growth, and to ensure that the storage of water is adequate for plant needs, and is not held too strongly or in pores too remote for it to get to plant roots.

The uncertainties about what was required of tillage, and the assumption that more and bigger meant better, led first to larger machinery and to more and more tillage. More powerful machinery has also allowed farmers to respond to economic pressures to cultivate the land even when it is in an unsuitable condition for tillage. Not surprisingly, fear has arisen that excessive use of large machinery is damaging the soil, certainly in the long term if not in the short term. It is easy to observe soil damage if soils are cultivated when they are too wet. As a result of the reduced yields in some parts of the country in the wet years of 1968 and 1969 an enquiry was set up to report on, amongst other things, the possible deleterious effects of more intensive management systems on potential soil productivity. The Strutt Report (1970) gave indications of damage that was thought might be occurring to some soils, but no specific physical measurements were presented to establish whether newer, or any, farming methods were causing damage or, if there was damage, whether this could be easily remedied or not.

To quote from the report: ‘Soil structure is another matter. . . Some soils are now suffering from dangerously low levels [of organic matter] and cannot be expected to sustain the farming systems which have been imposed on them. A whole range of soils is suffering too from the effects of the passage of heavy machinery over them in unsuitable conditions.’ Yields of wheat and many other crops were much lower in the wet year 1968, but have since improved and continue to follow a general upward trend, with the possible exception of sugar beet. The slight decline in sugar beet yields since 1968 could be due to structural damage, but by contrast potato yields have continued to increase. Thus crop yields provide no obvious evidence of irreversible damage. However, no account is taken of the extra expense involved in managing those soils made more difficult by damage. Of this the farmer alone is really aware. Nor does it take account of less apparent changes which may cause problems in later years. Of these the soil scientist should be aware, or at least seeking evidence to warn us of potential dangers. Changes in subsoil permeability are for instance among those of which the farmer may not be conscious for some years, and for which he must depend on advice from the soil scientist.

The present paper attempts to define what constitute short and long term changes to soil properties, to indicate what soils are at risk from more intensive cultivation techniques and what methods may be used on different soil types to repair or avoid the damage, and discusses techniques which need to be evaluated for establishing the optimum soil physical conditions which must be maintained if we are to preserve our soils in a condition where yet higher crop yields can be obtained.

Deterioration of soil structure

Structural descriptions

It is a reflexion on the values of the first half of this century that while our knowledge of physics and technology developed to the stage where we are now able to fly to the moon, we failed to develop the skills that allow us to measure the structure of the soil. A terminology for the description of the macro- and microelements of structure has been developed (Brewer 1964), though not universally agreed. This can be useful in providing qualitative assessments of structure, and perhaps structural change. However, the relation between structure as assessed by visual examination, and specific physical properties which relate to crop yields, is highly subjective. The existence of plough pans which restrict drainage and root penetration can be relatively easily demonstrated, as well as their unfavourable effects on plant growth. Such conditions were illustrated in *Modern farming and the soil* (figure 1). No quantitative data about their formation appears to be available, nor specifications of the soils in which they

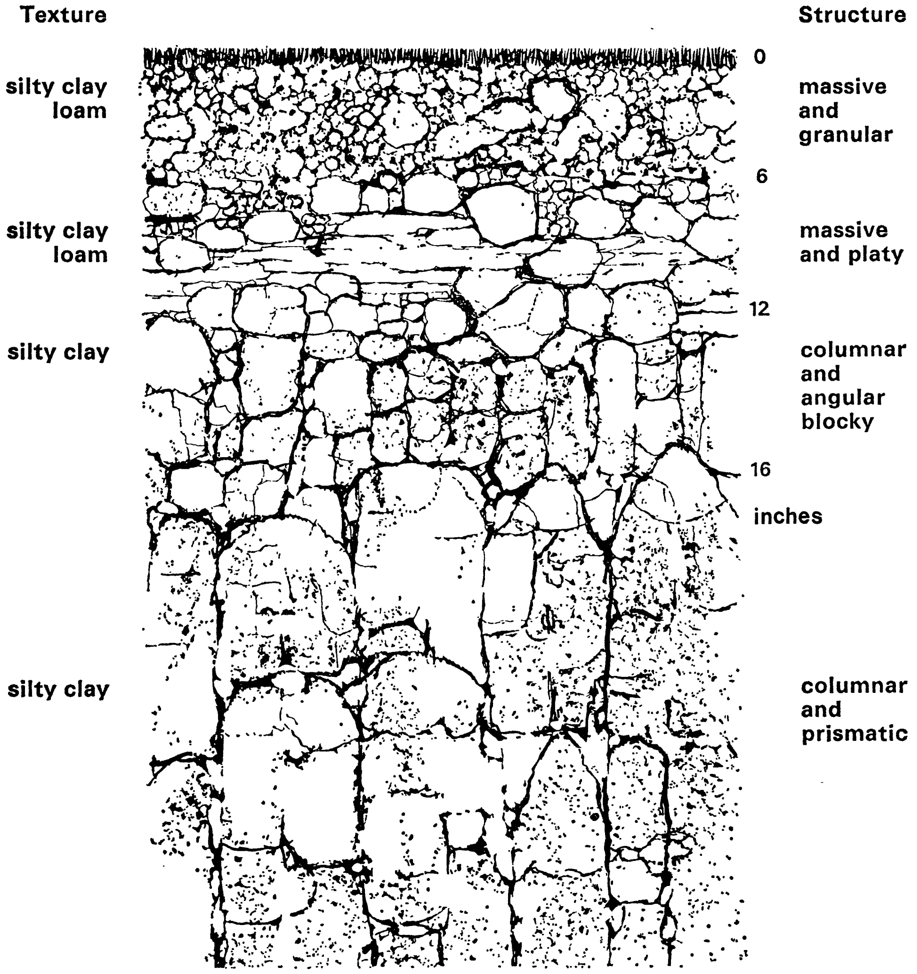


Figure 1. A typical, non-calcareous boulder clay profile, badly drained owing to fissures below 12 inches being blocked by mud which has flowed from the rounded tops of blocks and columns. The soil has slaked and formed a platy structured layer at 6–12 inches caused by ploughing and wetness. Taken from the Strutt Report (1970).

occur, nor information relating to how long it takes for them to be produced. Some work has been briefly reported (Swain 1975) which shows that when they are broken by subsoiling they can redevelop in a few years, but no methods have been described for determining from soil properties in which soils this will occur. Such a state of affairs will persist until precise quantitative descriptions of structure are available. The report of the Agricultural Advisory Council (Strutt 1970) rightly includes in its recommendations (p. 109): 'we urge soil scientists to direct their attention to defining tilths in exact physical terms.'

Table 1. Classification of soil pores

author…Manegold, quoted by Scheidegger 1957		Brewer 1964		McIntyre 1974		this paper	
e.c.d.†	name	e.c.d.	name	e.c.d.	name	e.c.d.	name
		> 5000	coarse macrovoids	> 3000	superpores		
> 100	voids	> 75	macrovoids			> 500	fissures
				30–3000	macropores	50–500	transmission pores
30–100	capillaries	30–75	mesovoids	0.2–30	minipores	0.5–50	storage pores
> 30	force spaces	5–30	microvoids				
		< 5	ultramicrovoids	< 0.2	micropores	< 0.5	residual pores
						< 0.005	bonding spaces

† e.c.d. = equivalent cylindrical diameter, in micrometres (10^{-6} m).

Pores larger than 50 μm e.c.d. are those which normally drain under gravity, and allow free air and water movement and root development. The water content when pores larger than 50 μm have drained corresponds to the field capacity of the soil. Wilting of plants normally commences when most pores larger than approximately 0.5 μm have emptied.

Structural definition and measurement

Soil structure may be defined as 'the arrangement of the soil particles and of the pore spaces between them' (Marshall 1962). Quantitative methods are available to define particle arrangements but are clumsy to use, and involve difficult conceptual processes if used to describe relations between soil properties and plant growth. It is simpler to concentrate attention on the soil pores rather than the structural units as such, for it is the pores which determine the physical properties important to plants. A simple subdivision of soil pores, with approximate relations to physical properties important to plant growth, is given in table 1. There is an enormous range in the size of soil pores. Some 10 % or more of the total porosity may be present as pores with equivalent diameters greater than 0.05 mm, and an equal volume may be present as pores with equivalent diameters less than 5 nm, a factor of 10^4 dividing them. The larger pores are critically important for transmissions of air and water, and the smaller ones are those where the interactions at the molecular level take place, and which are therefore critically important in terms of the forces holding domains and aggregates of primary particles together. Between these size limits are the pores which hold water sufficiently strongly not to drain readily under gravity, but still be able to release water to plants (approximately those 0.5–50 μm equivalent diameter) and a further group which rarely lose water in the field, and are probably important only as a reservoir of nutrient ions and in providing a medium for the action of interparticle forces.

It is somewhat surprising that no generally accepted terminology has been developed for soil pores in terms of function. In this paper it is proposed to use the terms transmission (50–500 μm), storage (0.5–50 μm) and residual pores (< 0.5 μm). The very fine pores important to particle interaction (< 5 nm) also merit specific recognition and the term 'bonding pores' is suggested.

Damage to soil structure mostly takes the form of a decrease in the proportion of pore space present in transmission and storage pores. This may give rise to a loss of total porosity, or it may arise from a change in pore size distribution, an increase in the volume of residual pores occurring at the expense of larger pores. Puddling a clay soil, which causes realignment of soil particles in a more open structure, often produces an increase in total porosity but a decrease in the volume of transmission and storage pores.

Measurements of the total porosity and pore size distribution are not themselves adequate to measure the properties of a soil important to gas exchange, water movement and storage, and root development. Continuity, tortuosity and resistance to deformation at different water contents are also important. To measure physical damage to a soil thus requires the changes in each of these pore characteristics to be determined.

Changes in total porosity and bulk density are relatively easily determined and provide a crude measure of compaction. Air filled porosity of clods at field capacity provides some measure of transmission pores, and is sometimes used to indicate the extent to which transmission pores have been lost. A more complete assessment of changes in the volume of different classes of pores is obtained if it is assumed that water is removed from pores of diminishing size as the suction supplied to the soil is increased (Childs 1969). However, for many of the heavier soils liable to damage, removal of water is accompanied by substantial shrinkage, and there is a lowering of the soil surface rather than a replacement of removed water by air filled pores. The extent of surface movement can be measured by relief metering, with the feet of the relief meter anchored at depths in the soil to the point where no movement occurs (Kuipers 1957). At the same time as surface lowering some fissures will normally develop, due to shrinkage in the lateral direction. In heavy clays the aggregates may continue to shrink until a suction of several atmospheres is reached, when air entry occurs (Lauritzen 1948). Thus the water content:suction relation cannot give any useful information about pore size and distribution in soils which shrink and swell significantly.

To obtain meaningful data relating to pore size distributions of such soils at different water contents, it is necessary to be able to remove the water from the soil at any given water content without altering the porosity and pore size distribution. The late Dr Robin Greene-Kelly at Rothamsted had been engaged on this problem for many years, and developed methods which reduced shrinkage substantially compared with direct drying (Greene-Kelly 1973). It is still necessary to improve these methods and to develop techniques for measuring the pores left empty without changing them. Mercury intrusion porosimetry offers the opportunity of obtaining pore size distributions relatively rapidly, but confirmation that mercury injection does not produce some collapse of pores is still required. It is also necessary to establish methods to quantify the data so that they refer accurately to significant areas of soil, very high variability in the field being a characteristic of most soils. Finally, it is particularly important that appropriate measurements of continuity of pores should be obtained. Optical methods (Dexter 1976), supported by flow studies, are probably most suitable for this.

Optical methods of study of porosity, pore size distribution and pore continuity are tedious, especially for the storage and residual pores, most of which are only visible using the electron microscope. The translation of the porosity of the microelements which can be seen, to flow characteristics on a macro-scale, has not yet been achieved. Quantimet techniques offer an opportunity for this, but it is probable that detailed optical studies will be at best semi-quantitative and therefore be a valuable aid to other physical studies, but not provide more than circumstantial evidence when or if employed on their own.

Stability of structure

The problem in the field is what changes are produced in porosity by different forces. These may include shear produced by machinery, compaction forces due to machinery or animals, or natural overburden pressure or rainfall stresses, for instance associated with the rapid wetting of previously dry soil aggregates. Although engineering data are available for many soils which demonstrate compaction and shear failure under stress, few data are available to show how much compaction affects pore size distribution. Our understanding of 'damage' due to badly timed cultivations or to compaction by too frequent passage of heavy machinery will be very unsatisfactory until we have succeeded in measuring such changes, and determining on what soils a real problem exists.

Fissures and macropores are most at risk as they are relatively weak, particularly in wet conditions. They are the pores formed between clods and aggregates, and are extremely important in terms of air and water movement. The attention focused on aggregate stability in earlier work on soil structure has its foundation in the fact that pores between aggregates will only persist when the aggregates have considerable stability. The factors giving rise to stability are now relatively well known (Baver, Gardner & Gardner 1972) and the major importance of organic matter established. However, the majority of soils have aggregates which are unable to withstand even weak forces when they are wet and can be made to coalesce to clods by pressure or smearing. Measurements of increased bulk density due to frequent passages of agricultural machinery over soils have been described by Davies, Finney & Richardson (1973), Soane (1973) and Spoor (1975) and a large volume of information relating to soil compaction has been assembled by Barnes *et al.* (1971). Passage over soils which are not too wet causes increased bulk density due primarily to loss of fissures and transmission pores. How far it is also due to loss of smaller pores when wet soils are cultivated has not been established.

Stability of clods and aggregates is not only important to the persistence of larger pores. Slaking of aggregates releases smaller clusters – microaggregates or domains of clay particles – which may themselves be packed into arrays containing only residual pores, and previously existing storage pores are lost. More importantly, individual clay particles may disperse and be carried into lower soil horizons where they can block transmission and storage pores. Thus stability needs to be measured in terms of resistance to slaking and dispersion, as well as in terms of mechanical stability to compaction and shear.

Structural damage: short term

Cloddiness

The loss of fissures and transmission pores in surface soils due to compaction will generally be a short term change. In some soils the natural processes of wetting and drying will induce stresses due to unequal swelling that will break clods into smaller aggregates. Freezing and thawing at the appropriate water content has been shown to act similarly (Richardson 1976; Yong & Warkentin 1966). Such natural 'mellowing' of tilth is a phenomenon well recognized by many farmers. The textural characteristics of soils in which it occurs regularly and the importance of previous management, of organic matter level and of seasonal severity have all to be determined. Wilkinson (1975) in discussing its occurrence in heavy soils in England indicates that it operates most effectively in calcareous clays.

In most soils farmers expect to have to produce a tilth from cloddy conditions by cultivation and considerable skill is often learnt in the design and use of machines for converting cloddy structures to finely aggregated ones suitable for seed beds (Spoor 1975; Patterson 1975). This means that loss of fissures and macropores can be relatively easily corrected.

Harshness

Continued intensive arable cultivation tends to give rise to harsh aggregates, lacking the 'mellow' condition. The low internal porosity of these aggregates (Currie 1966) appears to be primarily due to loss of storage pores, which hold water that is not lost by gravity drainage, and act as the main source of supply to plant roots. This internal porosity of aggregates is believed to be created mainly by biological, and particularly faunal, activity in the soil. Continuous arable agriculture causes a marked decline in such activity, and the aggregates in such soils are usually very hard, the dominance of fine pores making them strong when dry, and their shaping by implements giving them flat surfaces with sharp edges, rather than the softer, rounded outlines associated with biological activity. The inclusion of organic matter within the aggregates helps to give them stability to shear or compactive forces (Currie 1966) so that the softer aggregates of higher organic matter content, although more easily compacted, can often retain their identity better than the 'harsh' aggregates of lower organic matter content.

Once a harsh structure has developed, little can be done by cultivation to correct it. Short term leys will normally have some effect (Greenland 1971; Eagle 1975) and certainly longer term periods of pasture produce a radical change (Low 1955). Thus, although development of harsh aggregates of low internal porosity must be regarded as temporary rather than permanent damage, its cure can be a relatively long term operation.

Poaching

Patto (1975) has estimated that 23% of the land surface of England and Wales is highly susceptible to damage by 'poaching', the compaction of the soil surface under pasture due to trampling by animal hooves or other factors. As stocking rates have increased, so the extent of damage has increased, and it is now possibly the most widespread cause of structural problems in Wales and western England. On older pastures where aggregate and micro-aggregate stability is relatively high, the damage caused is likely to be loss of fissures and coarse pores in the surface soil, leading to temporary water logging. The high organic matter levels in such soils should normally be sufficient to prevent slaking and dispersion. Thus cultivation of the soil, or simply the activity of the soil fauna, should restore the surface structure quite readily. However, if the soil has been used for arable cultivation for some time, then aggregates are less stable and poaching may cause rather more serious problems due to loss of some storage as well as transmission pores, and because the effects may occur to greater depth. No critical data appear to be available, but Thomas & Evans (1975) suggest compaction occurs to 10 cm depth, and point out that to establish a surface tilth for reseeding can be successful, but may leave a compact, coarsely structured subsurface layer. Restoration of structure in badly poached short term leys may require several years of carefully managed grazing to allow root and faunal activity to influence the porosity to some depth. The importance of keeping an adequate cover of live grass over the soil by preventing too prolonged grazing has also been emphasized by Thomas & Evans.

As with other structural problems, soil texture and clay composition can also be important. Thus the light loamy sands (10 % clay) of the Frilford series at Hurley do not appear to be liable to serious damage (Clement 1975) and even prolonged periods under pasture have not resulted in significant structural changes. By contrast, the sandy loams of the Berkhamsted series at Jealott's Hill (18 % clay) lose macropores rather readily, but these can be restored by short term leys (Low 1975).

Capping

Harsh aggregates tend to be developed in heavier soils, and once formed the high clay contents make them relatively strong. In soils with higher contents of fine sand or silt, the aggregates are weaker, and their collapse under stress may lead to the formation of surface crusts or 'capping' (Davies 1975). The soil crust so formed is sometimes sufficiently strong when dry to prevent seedling emergence. Water entry may also be inhibited. Crusts are readily broken by light cultivation, and will not usually form if aggregate stability has been developed by a period under pasture.

Cultivation pans

Cultivation often smears the subsurface soil and may produce loss of porosity through a relatively shallow horizon (Frese & Altemüller 1962). This may also be due to particles and microaggregates released from the surface soil falling into pores in the lower horizon when a deeper pan is developed.

Development and redevelopment of cultivation pans appears to occur most frequently in silty soils of weak structure (Davies 1975) where packing of non-aggregated particles gives rise to horizons of very low permeability and high strength, and where there is less shrinking and swelling with change of moisture content than there is on heavier soils. The absence of fissures and transmission pores inhibits root penetration, so that organic matter which might convey stability to the fissures is absent.

Cultivation pans thus formed can be broken up by subsoiling, but the persistence of the improvement will depend on the stability of the pores and fissures created. However, if the factors producing the pan are eliminated by changing tillage practices, the effects of subsoiling should be more permanent, particularly if the surface soils are managed in such a way that slaking and dispersion of aggregates are avoided (Steinhardt & Trafford 1974). Development of cultivation pans should thus be considered as temporary rather than permanent damage in most soils.

Structural damage: long term

The most insidious form of structural damage arises from the movement of dispersed clay particles from surface horizons into macropores in subsurface horizons. This process occurs naturally in most soils which are not too acidic, and as a pedological process is described as lessivage. It is responsible for the higher clay contents of many subsoil horizons compared with surface soils. It occurs in its extreme form in the so-called solonetzic soils, where clays are dispersed and very mobile due to the effects of a high proportion of sodium among the exchangeable cations. Where calcium is the dominant exchangeable cation as in most British soils, clay movement occurs much less readily, and even the low concentration of electrolyte maintained in solution in equilibrium with calcium carbonate appears to be sufficient to inhibit dispersion (Rimmer & Greenland 1976) so that clay dispersion in calcareous soils is not normally important. However, in the absence of free calcium carbonate there is only a low energy barrier preventing calcium clays dispersing, and mechanical manipulation of wet calcium clays causes some particles to enter suspension. They may then be carried in suspension into the subsoil, where clay films develop, reducing the volume of transmission pores. Clay skins formed in this way may be recognized readily in thin section studies, and are a feature of many English soils.

At present it is not known how rapidly significant changes in subsoil properties can be produced, but it is known that the lower stability of aggregates of surface soils accompanying more intensive arable cultivation allows clay particles to disperse more readily. Thus there is circumstantial evidence to indicate that a problem exists. It appears that it may well contribute to development of cultivation pans. These can be broken up and so have only a temporary effect. A less easily cured effect arises when the transported clay is deposited through a considerably greater depth of soil. There is no immediately obvious cure for such effects, although long term pastures may be accompanied by root penetration into the subsoil, and generally greater biotic activity. Gradual remixing of surface and subsoil can then occur, but the process will take tens and perhaps hundreds of years to restore the former conditions.

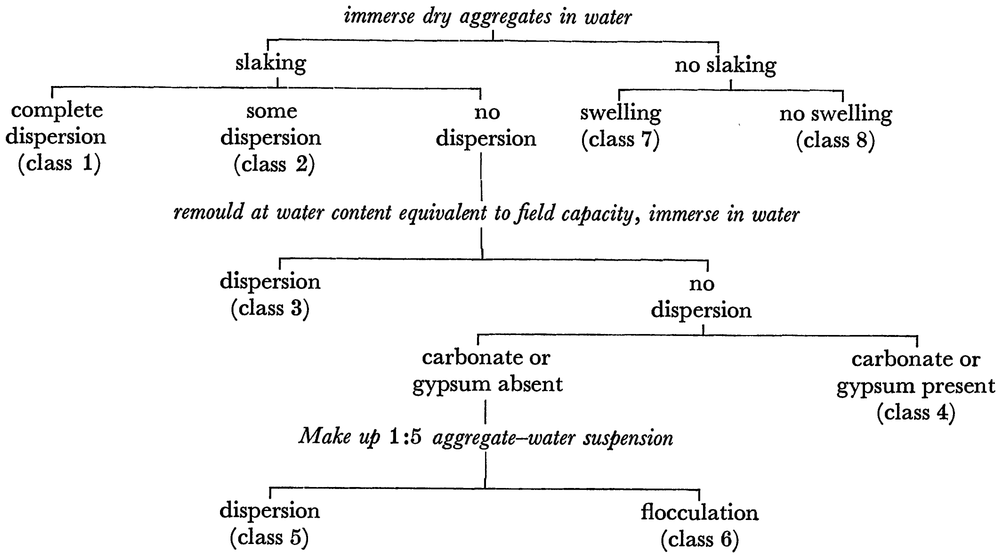
It is clearly necessary to develop a programme of experimental work to determine whether intensive arable cultivation in soils with dispersable clays is causing significant changes in subsurface permeability, and to obtain further data on the relations between slaking and clay dispersion produced by cultivations to drainage behaviour.

Classifying soils in terms of liability to damage

From what has been said above it is evident that structural damage can occur in a range of soils, and that the form it takes will differ in soils of different textural class. Damage is primarily in the form of loss of fissures, transmission or storage pores, and changes in pore continuity may also be important. Because the loss of these pores may give rise to an increase in the volume of fine residual pores, it is not necessarily measured by the increase of bulk density or loss of total porosity, although that is often an approximate guide. Damage will tend to be less in those soils where the transmission and storage pores, or, essentially the same, the aggregates and microaggregates, have a high stability. However, stability is always low when a soil is near water saturation (Gooderham 1973; Farrell, Greacen & Larson 1967), so that classifying soils in terms of stability is not sufficient to define those liable to physical damage. For instance many heavier soils of northern England and Scotland have relatively high organic matter contents and stable aggregates, but because they are often wet for prolonged periods tend to suffer from cultivation in wet conditions with resultant compaction and loss of transmission pores. This is temporary damage, relatively easily corrected.

However, subject to this limitation, a classification of soils in terms of their stability to forces causing slaking or dispersion is a useful guide to an assessment of what soils are liable to structural damage by intensive arable production. Emerson (1967) devised such a classification based on a simple visual test of the coherence of aggregates in water, and it has been shown that it produces realistic divisions of English and Welsh soils in terms of their known field behaviour (Greenland, Rimmer & Payne 1975). Many soils containing finely divided calcium carbonate, most containing more than 5% organic matter, and most of those with chloritic clays or clays containing a high proportion of fine aluminium and iron oxides, have a high stability and are unlikely to be permanently damaged by intensive cultivation. Those at risk, are generally of silty loam to clay texture, contain less than 5% organic matter, and have illitic or montmorillonitic clay fractions. Some fine sands and silts also are included. They fall in classes 3, 4, 5 and 6 of the Emerson classification (table 2).

TABLE 2. SCHEME FOR DETERMINING CLASS NUMBERS OF AGGREGATES (FROM EMERSON 1967)



The soils in classes 4, 5 and 6 slake but the clay does not disperse from the slaked fragments. Thus these soils are most likely to be damaged by loss of transmission and storage pores in the surface soil, but the subsoil should not be adversely affected by movement into it of dispersed clay particles. The clay fraction of soils in class 3 is liable to disperse if they are worked when wet (near field capacity). In these soils movement of clay into the subsoil may occur. Further, the dispersion of the clay following slaking frees the soil particles from aggregates, so that they can settle in close packing, with a resultant loss of the coarser pores. The packing will usually be sufficiently close for almost all pores to be in the 'residual' category, so that the soils then dry to compact clods, and the dispersed clay will cause dense, impermeable horizons to develop below the plough layer. The stability of such soils is affected by organic matter and it is clearly important that if possible they should be farmed in such a way that the organic matter level is maintained sufficiently high to prevent the soil entering class 3. Soils liable to enter class 3 through loss of organic matter should be identified and the critical organic levels established by appropriate field and laboratory studies, so that farming practices can be established which will avoid long term deterioration.

A few soils in Britain which have been affected by sea water at some stage in their history have high concentrations of sodium amongst their exchangeable cations and disperse spontaneously in water. These soils are extremely poorly structured, and require specific ameliorative measures to displace the sodium if they are to be brought into a condition where good yields can be obtained from them. The soils are placed in either class 1 or 2 depending on whether spontaneous dispersion is partial or complete; they are easily identified.

Improvement of soil structure

Correcting damage

Although there are several processes by which structure can be improved after it has been damaged, it is not always easy to apply the remedies. Intensive cultivation usually leads not only to loss of organic matter, and hence of stability of small aggregates and increase in strength of clods and compacted subsurface horizons, but also to the development of a less permeable subsoil horizon. This means that the topsoil remains wet for longer periods so that it is difficult to find periods when implements can get onto the soil without causing further damage. Conducting drainage operations or subsoiling in unsatisfactory conditions is well known to make the situation worse than before. What is needed is careful diagnosis of what damage has occurred, and selection of the most appropriate ameliorative measures. Those available for improving structure include:

cultivations,
subsoiling and mole and tile drainage,
exposure to natural weathering processes,
putting the soil to pasture to allow increased biological working, and
additions of suitable amendments.

Avoiding damage

As in medicine, prevention is better than cure, and good soil management will always be directed to avoiding undesirable soil compaction. Because of its immediate visibility, most attention is given to structural change in the surface soil, but cultivation causing clay dispersion and loss of subsoil permeability is probably a greater long term danger.

The first principle is to avoid machinery or large concentrations of animals moving over the land when it is wet, because in wet soils cohesive forces are low, irrespective of texture or organic matter content or clay constitution. Organic matter will give some resistance to compaction, but only when soils are sufficiently dry (Hamblin 1975). More importantly, organic matter will help to maintain soil aggregates and microaggregates intact, although they may deform. If the aggregates remain intact, movement of fine sand, silt and clay into subsoil pores is inhibited. Thus if the soil is managed in such a way that organic matter is kept at an adequate level, which generally means using a system of ley farming, permanent subsoil damage should be avoided, even if some traction occurs on wet soils.

If it is uneconomic to use leys, it becomes increasingly more difficult to manage the land so that traffic on wet soils is avoided. Minimum tillage and direct drilling techniques then offer considerable advantages in reducing the need for traffic to pass over the land. Although the bulk density of the surface soil initially increases when such methods are used, it has been widely observed that the soil fauna gradually increase in number under direct drilling, and the channels produced by worms increase the rate of air and water movement compared with conventionally ploughed and harrowed land (Cannell & Finney 1973). More information is required about the long term effects of such management systems, and the physical characteristics of both surface and subsoils. However, it appears likely that they offer considerable advantages in farming less stable soils more intensively.

On heavier soils, where natural drainage is poor, it is important that adequate drainage be provided to enable sufficient 'working days' for the soils to be used for arable production. Establishment of good drainage systems where needed is therefore an important aid to avoiding damage. However, they will only be useful as long as the soil is in a condition where sufficient flow to the drains can occur: transmission pores in surface and subsurface must remain open, and not be damaged by compactive forces, or filled by material released by slaking or dispersion. Transmission pores and fissures tend to close in clay soils rather readily due to swelling. Measures which reduce the swelling, such as the presence of lime, may help to maintain the subsoil permeability after prolonged wet conditions, but the swelling is necessary to produce fissures after drying.

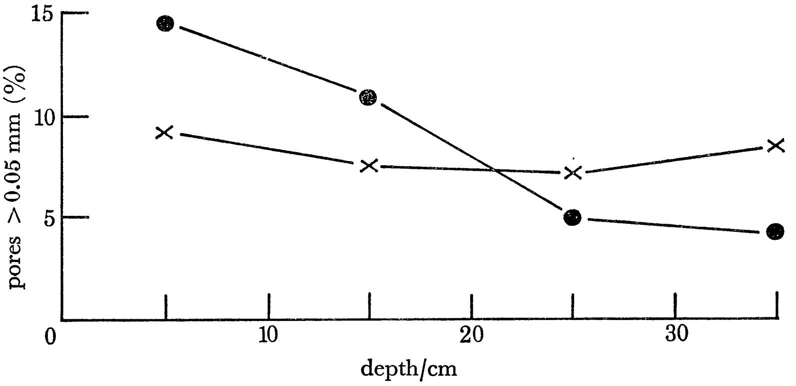


FIGURE 2. Transmission pores and fissures as per cent of soil volume, 3 months after direct drilling (×) and ploughing (●) a clay soil (Denchworth series). (Unpublished data of Mr D. Payne obtained on a tillage experiment conducted by staff of the A.R.C., Letcombe Laboratory at Compton Beauchamp.)

Organic matter, and particularly the polysaccharide component of it, is important in helping to maintain aggregate, and therefore pore, stability. Worm channels, and perhaps root channels, may be particularly stable because their walls are lined with mucilage. Tillage will destroy their continuity, but under direct drilling their persistence results in relatively high water conductivities which can counteract problems due to loss of other transmission pores.

Often the natural fissures and macropores in the subsoil are insufficient to carry water to drains at a rate necessary to increase significantly the time during which the soil can be safely cultivated. Creation of fissures by subsoiling may then be useful, but as mentioned previously, the success of the operation will depend on the stability of the fissures created. Recent evidence (figure 2) suggests that significant compaction and smearing of the soil layer immediately below plough depth can occur after only a single cultivation. The advantages of subsoiling will be rapidly lost if flow to the subsoil layer is interrupted at the plough sole. In some soils this arises from formation of a compacted layer with few transmission pores, or fissures, and in others by a reorientation of particles in a very thin layer, causing interruption of continuity of the transmission pores and fissures.

Soil conditioners

Most damaging effects occur where structural stability is low. If the economics of production make undesirable the use of leys for maintaining satisfactory organic matter levels and hence satisfactory stability, possibilities of the use of soil conditioners must be examined. These may take the form of bulky organic manures, which serve simply to prop the soil apart and maintain some temporary coarse pores. Their decomposition may yield some stabilizing agents which will bond existing soil aggregates together, and the biological activity supported by their decomposition may lead to the creation of some storage and transmission pores. The advantages of returning organic residues to the soil are well known and are discussed in Professor Russell's paper (this volume).

Recent work (reviewed by Carr & Greenland 1975*a*) has shown that the possibilities of using soil conditioners of the polyvinyl acetate and polyvinyl alcohol type also merit attention. Recent field experiments (de Boodt 1972; Oades 1976; D. B. Davies unpublished; C. M. Floyd, unpublished) and pot experiments (Carr & Greenland 1975*b*) have all demonstrated that where adverse physical conditions arise from structural instability these materials produce significant improvements. Little has yet been done to establish the economics of their use, and much further experimentation is needed to determine appropriate rates and methods of field application. At present it appears that they will have application for stabilizing drill rows in badly capping soils, and perhaps in stabilizing fissures after subsoiling or mole draining, to aid water flow to drains. The polyvinyl materials are resistant to microbial attack in the soil (Young & Harris 1975) so that the effects of one application are likely to persist for several years, if the continuity of stabilized pores is not lost through cultivation.

Establishing optimum conditions

To ensure maximum productivity it is not only necessary to be able to avoid or repair damage, but to be able to establish as far as possible those soil conditions which enable plants to grow to the limits imposed by photosynthetic rates. In terms of porosity this requires an adequate range of both macropores and storage pores, to a depth of 50 cm or more. Continuity of macropores should be such that water can flow freely to drains or into a freely draining subsoil. Optimum conditions in dry seasons arise from drainage systems which maintain a water table not too far below rooting depth, and where the soil contains a high proportion of storage pores. In wet seasons free drainage and a higher proportion of pore space as macropores or fissures will be required.

In terms of strength and stability the soil needs to have good resistance to compaction and at the same time low cohesion so that root proliferation, and for root crops, unrestricted storage organ development, can take place.

Management of the soil for optimum crop yields therefore involves some compromise. These are much more easily achieved when organic matter levels in the soil are adequate. When it is low because of continued intensive arable production, the limited range of water contents over which the soil is suitable for cultivation make it much more difficult to produce desired changes in the porosity of surface soils. It is possible also that stabilization of structural conditions with synthetic polymers will assist in maintaining optimum conditions for a period of arable cropping.

CONCLUSIONS

The purpose of this paper was to give some answer to the question whether damage to soils by increasingly intensive arable cultivation was temporary or permanent, and to assess whether we can expect to be able to cultivate our soils increasingly intensively, or whether on some we should restrain the frequency of cultivation.

On some soils structural stability is so high, and the structure so well suited to crop production, that no problems will arise. On others, temporary damage due to loss of transmission pores can arise, but this is readily corrected by appropriate cultivations. However, repairing damage becomes more difficult as organic matter levels fall, and attention needs to be given to the level of organic matter at which serious management difficulties are posed. Also in some soils of this class natural 'mellowing' processes can be important, and again we need to know more precisely what factors are important to natural structural improvement, and in what soils it occurs.

In some fine sandy clays and silts compaction and development of cultivation pans occur rather readily, and natural weathering does little to repair the damage. Cultivation, subsoiling and suitable drainage installations all help, but again are easier in soils of higher organic matter level. In many moderately heavy to heavy soils, as organic matter levels fall, aggregates tend to slake and disperse rather rapidly, particularly if the soil is cultivated when it is near field capacity or wetter. The soil will then pack tightly and fissures and transmission pores are lost. This means that the period when the land is dry enough to be worked satisfactorily is also reduced, and a cycle is likely to develop in which the soil is increasingly damaged and increasingly difficult to repair. If clay is translocated so that the macroporosity of the subsoil is seriously reduced in a soil where drainage is needed, the damage may be permanent. The extent of soils of this type is not at present known, but many of the non-calcareous clays may belong to it. The problem will be less serious if organic matter levels are above about 5 %. Again more research is needed to establish just which soils are at risk, and what are the critical levels of organic matter in different soil types.

In general there is a serious lack of knowledge relating to soil physical conditions and crop production. An appropriate analogy is with plant nutrition about a century ago, when we were just beginning to understand the importance of correcting specific nutrient deficiencies to improve plant growth. We are currently starting to be able to recognize certain specific adverse physical conditions in soils and devise methods for their correction. Because in some soils permanent damage may be done, it is rather urgent to devise suitable methods for recognition of these soils. Where temporary damage may occur, it is important that the advantages of less damaging methods such as minimal tillage and direct drilling are fully evaluated.

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Discussion

H. C. Pereira, F.R.S. (*Ministry of Agriculture, Fisheries and Food*, 10 *Whitehall Place*, *London SW*1). Would Professor Greenland agree that under the adverse conditions of a wet harvest, when surface soil has been puddled and slumped by crop lifting machinery and transport, a subsequent deep ploughing could do positive harm? It appears from the striking evidence which he has just shown us that deep cultivation while the surface is in poor condition has the effect of opening the major cracks and pore spaces in the subsoil to the downward leaching of fine particles of dispersed clay and silt. Soil profiles in which the subsoil channels are filled with fresh clay are real danger-signals. Farmers should be warned against deep ploughing as a restorative operation on a battered field.

D. J. GREENLAND. Yes, I entirely agree. While I am unaware of any direct evidence of favourable or unfavourable effects from deep ploughing of previously damaged soils, the evidence that we have relating to the general effects of ploughing indicates that any short term advantages associated with the opening of the surface soil are likely to be more than offset by the long term damage caused by allowing dispersed soil material to penetrate the subsoil.