Effects of green manuring in rotation with corn on the physical properties of two Québec soils

by

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ABSTRACT

M.Sc. Roderick John MacRae Renewable Resources

Effects of green manuring in rotation with corn on the physical properties of two Québec soils

Eight treatments were applied for a three-year period to a Bearbrook clay and a Franklin gravelly loamy sand in a rotation experiment which included corn and several green manures. Aggregate distribution, bulk density, moisture retention, and water flow were measured for each soil.

Incorporating red clover into the Bearbrook soil improved dry-aggregate distribution and reduced bulk density but did not increase the stability of aggregates in water. Infiltration did not improve in response to green manures. Physical parameters had less effect on crop performance than climatic and fertility factors. Incorporating common vetch and buckwheat into the Franklin soil did not affect any physical parameter differently from the monoculture-corn treatment though a laboratory study suggested that buckwheat was more suitable for producing aggregates. In general, row cropping proved detrimental to the soil physical condition. Significant correlations between independent parameters made it impossible to determine cause-and-effect relationships between corn yield and soil physical properties.

RESUME

M.Sc. Roderick John MacRae Ressources Renouvables

Les effets des engrais verts en rotation avec le maïs sur les propriétés physiques de deux sols du Québec

A l'interieur d'une rotation de trois ans incluant le maïs et des engrais verts, huit traitements furent appliqués à une argile Bearbrook et à un sable loameux gravelleux Franklin. La distribution granulométrique des aggrégats, la densité apparente, la rétention en eau, et l'écoulement d'eau furent mesurées sur chacun de ces sols.

Sur l'argile Bearbrook, l'enfouissement du trèfle rouge améliora la distribution granulométrique des aggrégats secs et diminua la densité apparente du sol. Par contre, la stabilité des aggrégats dans l'eau ne fut pas augmentée. Pour ce qui est de l'infiltration aucune amélioration fut notée. Ce sont les facteurs climatiques et la fertilité qui affectèrent le plus les récoltes, l'influence des paramètres physiques étant moins importante. Sur le sol Franklin, l'enfouissement de la vesce commune et du sarrazin n'affecta aucun paramètre physique différemment à la monoculture de maïs. Un étude au laboratoire a toutefois indiqué que le sarrazin produisait le plus d'aggrégats. En général, la culture en rangs fut nuisible aux conditions physiques du sol. Les corrélations significatives entre les paramètres indépendants font qu'il est impossible d'établir une relation de cause à effet entre la rendement du maïs et les propriétés physiques du sol.

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Suggested short title

Effects of green manuring on soil physical properties

MacRae

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INTRODUCTION

Corn has become a major economic crop in Québec. It is well known that conventional, continuous corn production is an agricultural system with intensive demands on the soil resource and production inputs. The soil organic-matter supply may be depleted in this system, and this may result in a poor physical condition and declining yields. The incorporation of green manures could alleviate these problems by supplying organic material and if used in a short-term cropping system could still allow for maximum use of land for corn production.

Green manuring is the process of turning a crop into the soil, whether originally intended or not, irrespective of its state of maturity, for the purpose of effecting some agronomic improvement. It is an ancient practice. The earliest references to green manuring date from the Han dynasty of China, prior to 1134 B.C. Lupines and faba beans were used by the Greeks as green-manure crops before the third century B.C. and the practice has continued in southern Europe since then. The adoption of green manuring occurred much later in northern Europe (Pieters, 1927).

Green manuring has existed as a farming practice in North America since the 18th century. Its popularity reached a peak in the first decades of this century at which time its practice was very widespread. The advent of cheap inorganic fertilizers resulted in its decline. Research effort has been minimal since the late 1950's and attempts to re-evaluate the usefulness of green manures have been hindered by a lack of recent information. Virtually no work has been done on green manuring in Québec.

The literature on green manuring on a global scale is voluminous and confusing. Joffe (1955) has explained the variability in green-manure research results with a zonality principle; the effectiveness of green manures is dependent on the climatic zone in which they are used. Literature cited in the thesis has been confined to the temperate world as much as possible. Also, the author has concentrated on studies involving field cropping systems, particularly those involving corn and green manures that were used in these experiments.

Several soil physical parameters have been used in this study to evaluate the impact of green manuring: aggregate distribution and stability, bulk density, water movement and moisture content and retention. Two soils with physical limitations to corn production have been studied, a Bearbrook clay and a Franklin gravelly loamy sand. Two green manures were used at each site and were chosen on the basis of agronomic suitability and economic potential. An attempt will be made to relate improvements in the physical condition of the soil to crop performance.

LITERATURE REVIEW

It is well known that there is a general relationship between soil physical properties and the amount of organic matter a soil contains. The general statement would be that, all other factors being equal, soil with high soil organic-matter levels has a good physical condition. "Soil organic matter refers to the organic fraction of the soil; it includes plant and animal residues at various stages of decomposition, cells (living and dead) and tissues of microbes, and substances synthesized by the soil population." (Canadian Department of Agriculture, 1972). Seldom does the addition or synthesis of such material not cause an effect on at least one soil parameter (Allison, 1973). If a green manure is capable of increasing the soil organic-matter level, then one would expect that the physical condition would be improved. The literature indicates, however, that i) organic matter does not directly affect all physical parameters; ii) green manures do not necessarily increase soil organic-matter levels and different plant species can vary widely in their effect; iii) green manures do not necessarily improve the soil physical condition even when total soil organic-matter levels are maintained or increased by green-manure addition and iv) if the soil physical condition is improved, there may not be an associated improvement in crop performance.

EFFECT OF ORGANIC MATTER ON PHYSICAL PARAMETERS

The properties most likely to be affected by increased organic-matter levels are aggregate distribution and stability, bulk density, moisture retention, and water movement, but the extent to which these parameters might be improved, and the conditions under which the improvement might occur, are not well-defined.

Aggregate distribution and stability

Martin et al. (1955) define a soil aggregate as a "...naturally occurring cluster or group of soil particles in which the forces holding the particles together are much stronger than the forces between adjacent aggregates." Aggregate formation and stabilization result from separate forces but often occur simultaneously. Few agents are involved in both processes.

Formation involves the orientation of soil particles into closer proximity with the result that physical forces of attraction are better able to hold the particles together. The dominant forces involved in formation include wetting and drying cycles, cycles of freezing and thawing and other temperature changes, cultivation, root pressures involved in plant growth, earthworm tunnelling, and animal trampling.

Organic matter plays a minimal role in aggregation. Only in sandy soils, and perhaps clays, does it have any effect. Decomposed fungal mycelia may form aggregates in sandy soils through physical entanglement, particularly after the addition of plant residues, as fungi are closely associated with freshly incorporated plant tissue (Kononova, 1966). Hartmann and De Boodt (1974) have found that sands of medium to high organic-matter content in the

Netherlands exhibited an aggregating pattern similar to a sandy loam soil. They, thus, attributed to organic matter a major role in aggregate formation in coarse-textured soils. In fine-textured soils, coarse organic material may prevent the formation of large aggregates by blocking the attractive forces between smaller aggregates. But in general, agricultural soils have sufficient opportunity for aggregate formation and insufficient stabilizing material. It is in this area that organic matter plays an important role.

Organic matter is the primary stabilizing agent in temperate soils. Specifically, it is the decomposition products of plant and animal residues that are responsible for aggregate stabilization: microbial gums and mucilages, low molecular weight fulvic-acid molecules and linear organic polymers like fats and waxes (Greenland et al., 1962; Harris et al., 1966; Allison, 1973).

Theories of stabilization mechanisms are numerous. The most widely accepted view is that of Emerson (1959), who described organic binding at a microscopic level. In his model, organic material of molecular thickness acts as a binding agent between clay micelles or clay and quartzitic particles. Infrequently, the organic material coats clay domains. A series of linkages between clay and quartzitic material results in a soil crumb. This model has not, as yet, been experimentally proven correct.

Emerson's model is applicable over a wide range of textural classes but may not completely explain aggregate stabilization in very sandy soils or clay soils. Soils of <10% clay content generally act as if non-aggregated (Allison 1973) and Emerson's model seems to support this. Pringle and Coutts (1956), however, found stable aggregates in a Scottish soil having 8.9% clay content and a loamy sand textural classification. In fine-textured soils, improving aggregation often involves the breakdown of large aggregates. In addition to the stabilization mechanisms that Emerson describes, large organic molecules, slightly decomposed and not part of Emerson's model, may be necessary to prevent slumping or the creation of a very finely divided system of aggregates (Greenland, 1965).

The highest percentage of stable aggregates is found in soils of high organic-matter content (Doyle and Hamlyn, 1960; Harris et al., 1966). Although this has been proven chemically, it is sometimes difficult to reach the same conclusion in agronomic studies. Greenland (1965) has indicated that organic carbon determinations may not correlate well with aggregate analyses because the total organic-carbon analysis commonly used in agronomic studies is not measuring just those organic materials responsible for aggregate stabilization. Chester et al. (1957) correlated soil gum and total organic-matter levels of silt loam soils in Wisconsin with aggregate stability and found only a slightly significant correlation with total soil organic matter, while soil gums were highly positively correlated to stability. De Kimpe et al. (1982) found no significant correlations between soil organic-matter levels and dry and wet-sieve a alyses in their study of 21 Québec topsoils. Coote and Ramsey (1983) did not find a significant correlation between organic carbon and wet mean weight diameter (MWD) in their study of four Ontario soils. These results could also be due to the inadequacies of sieving procedures (Harris et al., 1966).

In summary, organic matter is known to play a primary role in aggregate stabilization, although agronomic studies have not been able to suitably quantify the relationship. Organic matter plays a minor role in aggregate formation.

Bulk density

With few exceptions, organic matter decreases the bulk density of soil. This may occur directly by dilution of the soil matrix with a less dense material, or indirectly by improving aggregate stability. This effect does not seem to be limited to certain soil textural classes. It is the indirect improvement of bulk density, through the improvement of aggregate distribution and stability that is most important. Physical incorporation alone can affect detrimentally other physical parameters such as moisture movement (Jamison, 1960).

In a recent Québec study of 21 topsoils with organic-matter contents ranging from 1.6 to 11.9%, De Kimpe et al. (1982) found high negative correlations between organic matter and maximum bulk density after compaction. Millette et al. (1980), comparing cultivated (for 60 years) and forested Orthic Podzols, found a highly-significant negative correlation between organic matter and bulk density. Soane (1975) found organic-matter levels to be highly negatively correlated with bulk density in compaction studies. The correlation of texture with bulk density was not significant. Coote and Ramsey (1983), working with four Ontario soils of different textural class, found organic matter to be highly negatively correlated with bulk density in tillage studies.

Moisture content and availability

Organic matter improves available water-holding capacity of soils under specific circumstances only. It is the exception rather than the rule.

Peele et al. (1948) found significant correlations between organic-matter content in sandy loam soils of South Carolina and available water-holding capacity (AWC). Using their data, Jamison (1953) refined their conclusions.

He found the same significant correlations between organic matter and AWC in soils with less than 15% clay. With more than 15% clay, other factors were dominant in determining the AWC. Jamison and Kroth (1958) supported this finding with results from Mississippi soils. They found organic matter to influence AWC only in soils of medium-low clay content (13-20%). As they found AWC to increase with silt content, they suggested that the organic matter tends to help form stable micro-aggregates of coarse-silt size. Their conclusion was that coarse silt had the greatest influence on AWC. Reeve et al. (1973) also found significant correlations between coarse silt and AWC. They felt that organic-carbon levels were not a primary factor in determining what they refered to as available water (essentially AWC in mineral soils).

Although Singh (1962) claimed that organic material has a very high water-retention capacity, Jamison (1953) and Feustal and Byers (1936) have concluded that most of the moisture is held at potentials below -15 bars, thus unavailable for plant growth. Feustal and Byers (1936) found little to be gained by adding peat muck to a clay soil. Jamison (1953) found that adding 103 tonnes/hectare of peat to a silty clay loam improved AWC only slightly. He suggested that only in very sandy soils, with low AWC, might organic-matter additions improve the AWC, though the volume of material necessary to effect such a result might be too large to be agronomically feasible. Stevenson (1974) supported this conclusion below -1 bar pressure on a loamy sand when moisture content was determined volumetrically. He found no effect of adding peat to a sandy loam and a detrimental decline of AWC in a silt loam. The minimum required addition of peat was substantial, 10% by weight of soil used. Hartmann and De Boodt (1974), on the other hand, found that organic matter had no effect on the water-retention properties (or critical capillary depression in their study) of sandy soils with organic-matter levels ranging from 0.12 to 7.17%.

De Kimpe et al. (1982) found a positive correlation between organic matter and gravimetric water content at field capacity on a wide range of Québec soils. There was also a significant negative correlation between bulk density and organic carbon. Stevenson (1974) has shown that changes in gravimetric water content with organic matter are often not a function of improvements in moisture-holding capacity but rather a function of the lower bulk density and that moisture content has to be measured volumetrically to really evaluate the relationship. The correlation between organic matter and water content in the De Kimpe et al. (1980) study is likely a function of the relationship between bulk density and organic matter. Denis Coté (1982, unpublished seminar, Journée d'échange scientifique, CPVQ, May 5, Ste. Foy, Québec) in a summary of data on AWC in a variety of Québec soils found large increases in AWC with increases in organic matter in sands and loamy sands. Increases in organic matter had no effect in other textural groups except clay where AWC was slightly higher in clay soils having >6% organic matter. AWC was measured on a gravimetric basis. Bulk density values were not reported.

Improvements in other physical properties induced by organic matter sometimes increase water-holding capacity. Such is not often the case for aggregation. Jamison (1953) found increased aggregation in three soils of various textural classes to result in decreased AWC. This result was due, in part, to an increase in moisture retention at the permanent wilting point (PWP). Doyle and Hamlyn (1960) found similar results. Hillel (1980) showed that increased aggregation can decrease the micropore volume and decrease the water content at field capacity, thus decreasing AWC. Jamison has stated that only in poorly-drained clayey soils does increased aggregation improve AWC. He was of the opinion that the increased macropore space is part of the defined AWC in poorly-drained soils. He felt that plant responses to improved aggregation in soils was due to the increased rooting volume from which water could be taken and not improvements in water-holding capacity in a given volume. Tamboli et al. (1964) have found that aggregates with the greatest organic-matter content do not have the greatest moisture retentive ability. In bulk-density studies conducted in England and Wales, Reeve et al. (1973) found that bulk density correlated negatively with available water in A horizons of silty soils only. B and C horizons had negative correlations in all textural classes, however, not all correlations in this study were significant.

Water movement

Organic matter has a strong effect on infiltration of water into soils. Wischmeier and Mannering (1965), working with 44 Corn-Belt soils with organic-matter contents ranging from 1 to 14%, found that, of all variables examined, organic matter was the most closely correlated with increases in infiltration. Textural differences had little influence. The reason for this relationship is somewhat unclear.

Allison (1973) stated that, when well mixed in the soil, organic matter greatly aids infiltration by providing better aggregation and structure, consequently lowering bulk density and easing water movement. The results of Coote and Ramsey (1983) are in agreement as they found a high negative correlation between infiltration and wet MWD. Martin and Richards (1969) found, however, that increases in aggregate stability did not necessarily result in increased hydraulic conductivity in a sandy loam aggregated by various bacterial polysaccharides. In fact, improvement in hydraulic conductivity was noted in some cases without an increase in aggregate stability. Wischmeier and Mannering (1965) found similar results; the aggregation index for wet aggregates was poorly correlated with infiltration ($r^2<0.10$) even though organic matter was highly correlated with infiltration.

In some sandy soils, decreases in infiltration are desirable and organic matter plays an important role in this. Working with a synthetic sandy loam, Barley (1954) found coarse organic material to decrease permeability. These results confirmed those of a previous study (Barley, 1953) in which permeability decreased as the coarse organic-matter content of a sandy loam soil increased in the surface 7.5 cm from 0.6 to 2.2%.

De Kimpe et al. (1982), found that organic matter had little, if any, effect on the saturated hydraulic conductivity of soils in a state of maximum organization or maximum compaction. Their study did not determine the relationship between organic matter and saturated hydraulic conductivity for spatial arrangements normally found in the field as did the studies mentionned above.

EFFECT OF GREEN MANURES ON ORGANIC MATTER LEVELS

It is generally accepted that green manures will maintain or increase organic matter or maintain or increase soil N levels but rarely both at the same time (Allison, 1973; Warman, 1980). Joffe (1955) stated that green manures were originally used as fertilizer; they were not perceived as a means to increase the organic-matter content of the soil until the late 19th century and the trend towards a specialized and mechanized agriculture. Pieters (1927) felt that the most important function of green manuring was to increase soil organic-matter levels though he later modified this, concluding "...that in the main the object of green manuring must be to maintain rather than increase the quantity of organic matter in soils." (Pieters and McKee, 1938). Some have not accepted that green manures can even maintain organic-matter levels (Pinck et al., 1946; Poyser et al., 1957). Russell (1973) maintained that on a global level green manure has been much more effective as a N source than as a source of organic matter. Most researchers will at least concede that green manures will affect the rate of loss of organic carbon in cropping systems and its ultimate level in the soil.

The maintenance or accumulation of organic matter in soil is dependent on a number of factors such as the chemical nature of the added material, soil and climatic factors as they affect microbial activity, and cultural practices. The popular conclusion is that a plant material resistant to ready decomposition is necessary if soil organic-matter levels are to be maintained or increased. Warman (1980) stated that plant material typically low in nitrogen, i.e. 1.5% N or less on a dry-weight basis, can be effective in improving the organic-matter content of a soil. A survey of complementary cropping-system studies, however, is inconclusive regarding the effect of plant nitrogen on organic-matter maintenance or accumulation.

From the literature on leguminous and non-leguminous green manures, there is no clear-cut relationship with regard to organic-matter accumulation and N content. Prince et al. (1941), in a 40-year potting study, found that vetch, incorporated two years in a five-year rotation of corn, oats, oats, wheat, and timothy did not maintain the organic-matter content at its original level.

Poyser et al. (1957), working with clay soils in Manitoba, found the organic-carbon levels in the soil to decrease across all treatments over a 25-year period. Losses of organic carbon in a green manure-wheat-corn-wheat rotation ranged from 30.7% for sweet clover to 6.1% for peas. Losses from non-leguminous green-manure treatments were slightly greater, ranging from 37.8% to 26.3%. Chater and Gasser (1970), working at Rothamstead on a sandy loam soil, found trefoil, incorporated each year between 1936 and 1965, to increase organic-matter levels significantly, by 18.7%. Ryegrass, incorporated yearly over the same period, did not increase soil organic-matter levels to the same degree, even though more organic material and less nitrogen were added over the course of the experiment. Mann (1959), working at Woburn Experimental Station in England, found, during 18 years of green manuring with legumes and non-legumes, that the manurial value was not directly connected with the N levels of the plant tissue or with the total amount of organic material buried. Allison (1973) reached the same conclusion with regard to amount of material buried but disagreed with Mann's conclusions on tissue N levels. De Haan (1977), working with a sandy and a clayey soil in the Netherlands, found no correlation between the % N of the added tissue and the amount of organic matter accumulated over 10 years, though he did find highly significant correlations with the % lignin of the original material. Leuken et al. (1962), working with Saskatchewan clayey soils, concluded that nitrogen was very important in determining the degree of organic-matter accumulation.

These different results are likely a function of other factors affecting organic-matter accumulation. Any soil factor that is likely to affect the soil microbial and faunal populations is likely to have an effect on organic-matter maintenance or accumulation. These include such factors as pH, soil N levels, native soil organic-matter levels, soil moisture, temperature, and exchangeable cations. The following study provides an example. Sowden and Atkinson (1968) applied annual additions of the same leguminous and non-leguminous green manures to Uplands sand and Rideau clay. Besides textural differences, the soils differed in pH (the clay soil was quite acidic), initial organic-carbon level (the sand had approximately one half that of the clay), and initial soil N (the clay had almost twice as much as the sand) (Sowden, 1968). After 20 years, they observed on the clay soil a loss of organic matter on the control and rye green-manure plots. All other treatments maintained soil organic-matter levels. On the sand, only the control plot lost organic matter; all other treatments increased organic-matter levels.

The authors did not try to explain which factors and their interactions might have been responsible for the different responses, but De Haan (1977) concluded that clay content is not a significant factor in determining the amount of organic matter formed. pH was a highly significant factor in his studies. In the Sowden and Atkinson study, the lower pH of the clay soil likely slowed the rate of organic-matter decomposition. Normally, organic matter would then accummulate. As it did not, other factors were of greater influence. Several authors have postulated that, in arable soils, an equilibrium soil organic-matter level exists (Jenny, 1930; Joffe, 1955; Allison, 1973). If this is so, the initial soil organic-matter level may affect the rate or amount of accumulation of new organic material. According to this theory, the power of cultivation to reduce organic-matter levels is much greater than that of any cultural practice that attempts to increase the organic-matter level of the soil. But once a cultivated soil reaches its equilibrium level, Joffe (1955) has stated that no management practice can lower it and it would be more feasible for incorporation of plant material to increase soil levels. It is possible that the sandy soil in Sowden and Atkinson's study was closer to this equilibrium level than the clay soil. If a soil has not reached that equilibrium level, organic-matter additions may be able to retard the rate of decline or may, as some have suggested (Broadbent and Norman, 1947), increase the decomposition of the native organic matter, a process known as "priming". Priming would actually increase the rate of decline. Allison (1973), however, reviewed the literature on this effect and concluded that it is insignificant in the course of a growing season.

Low soil nitrogen levels will affect the rate of decomposition and the amount of material that decomposes, depending of course on other soil and climatic factors and particularly the N content of the material being added. Generally, low soil N levels will result in a slower decomposition of organic material but, over the long term, there is potential for greater accumulation. The work done by Sowden and Atkinson demonstrates this result.

Green manures will affect soil organic-matter levels and many factors play a role in determining what that effect will be. There is agreement on what the major factors are but not necessarily on which factors exert the most influence, of what magnitude the effects will be and how they interact. The conclusions of Allison (1973) and Warman (1980), outlined at the beginning of this section, are appropriate only when all these factors are controlled.

EFFECTS OF GREEN MANURES ON PHYSICAL PARAMETERS

Green-manure studies have usually been performed independent of the general examination of how organic matter affects physical properties. It is, thus, important to see if both have produced the same results.

Aggregate distribution and stability

Although Ram and Zwerman (1960) have reported that aggregate stability "...is positively correlated with the quality and quantity of organic material added to the soil...", an examination of their citations and other work reveals that effects and effectiveness vary with soil texture and green manure used and that effects do not last long unless continuous additions are made.

Silt loam soils seem to be the most responsive to aggregate-stability increases from green manuring (Browning and Milam, 1944; Chester et al., 1957; Wisniewski et al., 1958; Ram and Zwerman, 1960). Effects are more variable in clayey and sandy soils with seemingly little association between increased aggregate stabilization and green manure used, frequency of incorporation, or number of years incorporated. Browning and Milam (1944) found increased aggregate stability in a silty clay loam but suggested that effects would be minimal in clays and in sandy soils. Mortensen and Young (1960), working with a silty clay in Ohio, found only transient improvements in aggregate stability attributable to the action of grass green manures. The clovers used in the study had no significant effect. Guttay et al. (1956) found no improvement in aggregate distribution or stability in a Michigan loam soil from biannual additions of sweet clover. Bowren and Wilson (1959), on the other hand, working with a Saskatchewan fine sandy loam, found a three-year rotation of sweet clover, wheat, and oats to have larger dry aggregates than a fallow-wheat-oats rotation and more water-stable aggregates in the top 15 cm (Bowren and MacNaughton, 1967).

Work done with a sandy loam in New Jersey by Benoit et al. (1962) indicates that several years of annual additions may be necessary before aggregate stability increases (three years in their study). They used ryegrass and found that incorporation of tops alone did not improve aggregate stability. It is not clear from their study whether the structural improvements caused by green manuring occurred continuously over a three-year period. The effects may have been transitory. Halstead and Sowden (1968) did not find ryegrass to increase the aggregate stability of a Rideau clay after 20 years of annual additions. Alfalfa as a green manure increased the aggregate stability somewhat and an increase in organic carbon was associated with this improvement. The strength of the association was not determined. Rennie et al. (1954) found that more readily-decomposable incorporated material (legumes) produced more stable aggregates in the very short term in a laboratory study, but that non-leguminous plant material produced effects that were more persistent. That all the field studies mentionned above did not reach the same conclusion is likely because of the multitude of factors, previously described, that affect decompostion of organic matter.

Bulk density

The addition of organic materials to a soil zone will automatically decrease the bulk density of that zone because the added material is of lower density than the soil matrix. The material used to effect such a result is largely inconsequential. Morachan et al. (1972) found no difference between alfalfa and corn stalks used to lower the bulk density of a silty clay loam subsoil. They felt the result might have been due "...partly or totally to the physical incorporation of the chopped residue." Their study did not take place over a sufficient time period to evaluate the effects of the respective decomposition products.

The relationship between an improved aggregate condition and an improvement in soil bulk density is theoretically straight forward but agronomic results do not consistently confirm this. Mortensen and Young (1960) did not find any change in the bulk density of a silty clay in the first growing season due to addition of various green manures even though the aggregate stability of the soil was higher. In a companion study, there were bulk-density effects due to green-manure treatments, that were not simply a function of dilution (alfalfa and red clover were more effective in reducing bulk density than yellow sweet clover, ryegrass, and orchard grass) but there were no effects on aggregate stability. Ram and Zwerman (1960) did find differences in aggregate stability associated with bulk density changes, as did Benoit et al. (1962).

There are also differences in the amount of time required to show effects and the duration of these effects. As mentionned above, Morachan et al. (1972) found effects immediately after incorporation but this was thought to be a purely mechanical effect. Mortensen and Young (1960) found two years had to pass before effects were apparent. Ram and Zwerman (1960) found bulk density was lower during the first two years after incorporation but increased in the third. Benoit et al. (1962) found three successive years of ryegrass additions were required before a decrease in bulk density was apparent but it lasted for the following three years. De Haan (1977), in a potting study, found all green manures used in his experiment, applied annually for 10 years, to decrease bulk density, particularly in sandy soil. Bowren and MacNaughton (1967) found that there were no differences between two rotations of three-year length after 28 years of cropping on fine sandy loam in Saskatchewan. The rotations differed one year in three as one contained sweet clover as green manure, the other lay fallow. There were differences, however, in aggregate stability. Hageman and Shrader (1979) found no significant differences in bulk density in a 20-year comparison of continuous corn and a corn-oats-meadow-meadow (as green manure) rotation. They attributed this result, in part, to the location of the sampling area in the continuous-corn plots. These areas did not receive any compaction. This suggests that degree of traffic and compaction may be a major factor in bulk density studies. The studies mentionned above do not discuss the amount of compaction experimental units received and if there were differences between treatments due to the management system. One can speculate that more information in this area would provide more consistency in the published results.

Moisture content and availability

The literature is sparse regarding the relationship between green manures and soil moisture properties. What exists suggests that moisture retention may be improved in sandy soils. This is consistent with literature discussed earlier in connection with organic matter.

Singh (1962) and De Haan (1977) have suggested that the total moisture-retention capacity of sandy soils will be increased by a variety of organic materials. De Haan did not find improvements in the clay soil he studied in a potting experiment. Singh stated that the organic material that results from green-manure additions is not colloidal in nature and therefore cannot improve the water-holding capacity of most soils. This is likely true in the short term but in the long term all organic material added and decomposed becomes colloidal. It is possible that aerobic conditions in sandy soils result in more rapid decomposition than occurs in finer textured soils (Allison, 1973), and this produces an organic material in the soil that has a more favourable water-holding capacity.

Ram and Zwerman (1960) attributed a higher soil moisture content to treatments with cover crops but their study did not indicate whether this moisture increase was plant available. In light of conclusions drawn by several authors mentionned above regarding the availability of water held by organic material, their findings are not of much value.

Morachan et al. (1972) found increased water-holding capacity in a silt loam soil with increased amount of residue added (the maximum addition was 16 t/ha). Ram and Zwerman (1960) found that, although they had significant results on a gravimetric basis, they did not on a volumetric one. Morachan et al. (1972) did not do a volumetric determination. This might have changed their results and conclusions as Jamison (1953) and Stevenson (1974) have indicated.

Water movement

Most of the work on the effects of green manures on water movement has been carried out on irrigated lands of the southern United States. Little has been done on the more northerly temperate soils.

Several authors have reported favourable improvements in infiltration and hydraulic conductivity when aggregate stability was also improved (Browning and Milam, 1944; Benoit et al., 1962). Browning and Milam concluded that increased stability in the macro-aggregate size range was of primary importance in effecting this result. Joffe (1955) concluded from his review of green manures in temperate soils that physical incorporation is also beneficial for increasing infiltration. Browning and Milam (1944) agreed. Jamison (1960), however, pointed out the limitations of physical incorporation. His study showed that isolation of soil zones can result with a decrease in moisture movement and air permeability that can cause yield decreases. Morachan et al. (1972) did not see any improvement in infiltration due to physical incorporation of various amounts of various residues.

The paucity of green-manure experimentation in northern climates makes it difficult to conclude whether results are consistent with more general work on the organic-matter-physical-property relationship. Few of the authors that have done work have properly examined the relationship between green manures, organic matter, and physical parameters. In general though, there is some consistency with results discussed in the previous section.

EFFECT OF GREEN MANURES ON CROP PERFORMANCE RELATED TO IMPROVEMENTS IN THE SOIL PHYSICAL CONDITION

Undoubtedly, improvement in the soil physical condition provides the opportunity for increased crop growth. This is an accepted fact. It is difficult, however, to assess quantitatively the degree of improvement, associated with green manures and organic-matter levels, necessary to effect a significant corn-yield increase, or which physical parameters have the most marked influence on corn production, and under what conditions yield increases will occur.

Most authors that have reported on the interaction of green manuring with corn yields have found increased corn yields associated with improvements in the physical condition but have been unable, because of experimental design, to differentiate the effect of improved fertility status from the improved physical environment (Guttay et al., 1956; Bowren and MacNaughton, 1967; Halstead and Sowden, 1968; Guernsey et al., 1969; De Haan, 1977; Sheard, 1977).

Sopher and McCracken (1973) have made a comprehensive attempt to determine the relationships between a variety of soil factors and corn yields. Using standard regression techniques, they attempted to determine cause-and-effect relationships between a variety of factors, including organic-matter levels and available-water capacity, and corn yields. Because of the high correlations between independent variables, however, they were unable to sufficiently define the factors of greatest importance.

Strickland (1951) and Morachan et al. (1972) found no correlations between physical improvement in silt loam soils and corn yield. They both concluded that the physical condition was not limiting to yields on the soils used. Page and Willard (1947) did find significant positive correlations between aggregate stability and corn yield in several clay soils of Ohio. Strickland suggested that effects would be more apparent on clay soils than on silt soils. Dirks and Bolton (1980), working with a clay soil in Ontario, did find bulk density to have substantial indirect and direct effects on yield of grain corn. Compacted soil reduced nutrient uptake and root growth. Fertility factors also played a major role in determining yields.

Others have concluded that physical properties will only significantly affect corn yield in years of abnormal total moisture. De Boodt et al. (1953) found no significant correlations between corn yield and any physical property affected by green manuring of sweet clover in a corn-oats rotation. This result was attributed to a sufficient moisture supply in the year the correlations were determined. Yield differences were thought, thus, to be caused by fertility factors. Benoit et al. (1962) found significant correlations between corn yield and aggregate stability of a sandy loam only one year in four and attributed this result to adverse weather conditions in that year. Mortensen and Young (1960) found aggregate stability and aeration porosity to be positively correlated to the number of corn plants per hectare, ear count, and yield of corn in a dry year only. They concluded that the improved soil structure aided germination. Due to the design of their study, their results are most likely a correlation of VAMA-improved, rather than green manure-improved, aggregate stability and aeration porosity with corn yield. De Boodt et al. (1961) concluded that significant correlations of soil structure with crop yield are weather dependent.

MATERIALS AND METHODS

Two soils were used in this study: a Bearbrook clay of the Gleysolic soil order, situated at Rigaud, Québec, classified 3^W in the Canada Land Inventory System; and a Franklin gravelly loamy sand of the Podzolic soil order, located near Rockburn (Blair Farm), Québec, classified 5^P_S in the Canada Land Inventory System. The Bearbrook clay soil was in grass pasture for at least five years prior to the commencement of the experiment. The Franklin gravelly loamy sand soil supported small grains for several years prior to 1978 but did not have any crops on it from 1978-1980, though it was cultivated periodically. Some physical and chemical properties of the two soil series are presented in Tables 1 and 2.

The statistical design at each site was a randomized complete block with eight treatments and three blocks. The treatments used at each site consisted of three-year rotations (Table 3). At the Rigaud site, sweet clover (Melilotus officinalis L.) and double cut red clover (Trifolium pratense L.) were intercropped with barley (Hordeum vulgare L.) while corn (Zea mays L.) was intercropped with white Dutch clover (Trifolium repens L.) in 1980 and common vetch (Vicia sativa L.) in 1981 and 1982. At Blair farm, corn was intercropped with 'Plowdown', a commercially-prepared green manure containing 60% sweet clover, 20% red clover (single cut), and 20% ryegrass (Lolium perenne L.), in 1980 and vetch in 1981 and 1982. All corn was harvested as silage, barley as grain. Corn and barley stubble were incorporated with the associated green manure. Each experimental unit was 300 m^2 in size at Blair farm and 200 m^2 at Rigaud. These plot sizes were chosen in order to simulate a farm scale operation.

Table 1. Some physical and chemical properties of Bearbrook clay

	Depth (cm)	
	0-10	10-20
Soil separate (% by weight)		
sand	18±5	14±4
silt	31±4	31±5
clay	51±4	55±4
Extractable P (ppm)	26.5±6.5	
Extractable K (ppm)	312±32	
Extractable Ca (ppm)	2370±570	2380±520
pH	5.2±0.6	5.1±0.2
Organic carbon (%)	2.45±0.58	1.24±0.65
Bulk density (Mg/m^3)	1.07±0.17	1.35±0.16
Aggregation index (AI)	512.8±30.6	545.2±34.6
Gravimetric water content at -0.1 bar (%)	48.6±4.1	39.8±0.5
Drainage class	imperfect	

Table 2. Some physical and chemical properties of Franklin gravelly loamy sand

	Depth (cm)	
	0-10	10-20
Soil separate (% by weight)		
coarse fragments	39	
sand	51±2	53±4
silt	6±2	6±1
clay	4±1	2±1
Extractable P (ppm)	87.9±21.1	
Extractable K (ppm)	117±22	
Extractable Ca (ppm)	1310±140	
pH	5.3±0.3	5.2±0.2
Organic carbon (%)	1.94±0.56	
Bulk density (Mg/m^3)	1.60±0.14	
% Aggregation (sand excluded)	38.27±6.87	
Gravimetric water content at -0.1 bar (%)	11.1±0.4	
Drainage class	rapid	

Table 3. Treatments applied on Bearbrook clay and Franklin gravelly loamy sand

Treatment	Year 1980	Year 1981	Year 1982
		Bearbrook clay	
A	corn	corn	corn
E	red clover/barley	corn	corn
G	corn	red clover/barley	corn
B	corn	corn	red clover/barley
C	sweet clover/barley	corn	corn
H	corn	sweet clover/barley	corn
F	corn	corn	sweet clover/barley
D	w. Dutch clover/corn	vetch/corn	vetch/corn
		Franklin gravelly loamy sand	
A	corn	corn	corn
D	buckwheat	corn	corn
B	corn	buckwheat	corn
C	corn	corn	buckwheat
H	Plowdown	corn	corn
G	corn	vetch	corn
F	corn	corn	vetch
E	Plowdown/corn	vetch/corn	vetch/corn

FIELD EXPERIMENTS

Bearbrook clay

Agronomic information is presented in Tables 4 and 5. The site was limed in 1980 at a rate of 5 t/ha $CaCO_3$ equivalent. Fertilizer rates were deliberately set below recommendations at the beginning of the study (Anon., 1978) to accommodate an associated fertility study. Inherent soil K values were extremely high, so K application was higher than recommended. No recommendations were available for pure clover stands.

In 1981 treatments A, C, and E were randomly split into 4 sub-plot units receiving varying rates of N fertilizer (Table 4). Sub-plot 4 received the same fertilizer rate as the main-plot units. In 1982, treatments A, C, E, G, and H were divided for sub-plot fertilizer application. P fertilizer levels were increased in 1981 as some P deficiencies were apparent in the corn in 1980.

Excessive moisture conditions affected field operations in 1980 and 1981. Corn (Warwick w-777) could not be removed by machinery in the fall of 1980, so it was removed with machetes. A wet June 1981 caused poor germination of the corn crop. Approximately 50% of the area was reseeded in mid-June. Cultivation, the primary weed control method, proved to be very difficult and not all experimental units received complete cultivation coverage. Atrazine was used for weed control at a rate of 1.1 kg active ingredient/ha in 1980 but proved to be ineffective. Higher dosages were deemed inadvisable because of the possible residual effects on clover and barley in following years. Clover and barley seeding rates were increased in 1981 to better compete with weeds.

Table 4. Field practices on corn plots, Bearbrook clay

		Year		
		1980	1981	1982
Site preparation		20/04-22/05	27/04-05/05	07/05-13/05
Seeding date		23/05	23/05+15/06	23/05
rate (seeds/ha)		61,800	59,000	60,000
Fertilizer (kg/ha) ($N-P_2O_5-K_2O$)	side dress	33-66-99	1 0-100-100	as 1981
			2-4 50-100-100	
	top dress	107-0-0	3 50-0-0	as 1981
			4 100-0-0	
	total	140-66-99	1 0-100-100	as 1981
			2 50-100-100	
			3 100-100-100	
			4 150-100-100	
Harvest date sub-sample		15/09	19/09	24/09
total		21/10	01/10	16/09

Table 5. Field practices on intercrop plots, Bearbrook clay

		Year		
		1980	1981	1982
			Clover/barley	
Seeding date		24/05	19/05	19/05
Seeding rate (kg/ha)	clover	16.5	18.9	as 1981
	barley	64.0	80.0	as 1981
Fertilizer (N-P_2O_5-K_2O kg/ha)		67-100-100	as 1980	as 1980
Barley harvest date		22/08	14/08	17/08
			Corn/white Dutch clover or corn/vetch	
Seeding date				
	corn	23/05	23/05+15/06	23/05
	clover	24/05		
	vetch		03/07	23/05
Seeding rate				
	corn (seeds/ha)	61,800	59,000	60,000
	clover (kg/ha)	16.5		
	vetch (kg/ha)		23.1	180.0
Fertilizer (N-P_2O_5-K_2O kg/ha)		140-66-99	50-100-100	as 1981

Common vetch replaced white Dutch clover in 1981 as it did not establish well in 1980. The seeding rate was then increased in 1982, and the time of seeding changed, as the 1981 stand was very sparse. Bruce barley replaced Laurier, used in the first 2 years, in 1982 as Laurier was no longer available.

Corn yield was calculated on a per-plant basis and multiplied by the stand density. Barley grain yield and green-manure biomass were determined on an area basis. All sampling was done from three random locations within each experimental unit. The 1982 corn crop was incorrectly harvested by machine before sampling for silage had occurred, so 312 whole plants that were missed by the harvester were collected, representing approximately 20% of the total that would have been collected. Only 65% of the units, both main and sub-plots, had salvageable corn. These data were used to estimate yield.

The site was plowed in late October or early November each year with green manures sampled for characterization just prior to incorporation.

Franklin gravelly loamy sand

Agronomic information is presented in Tables 6 and 7. The 'Plowdown' did not prove viable under the Franklin soil conditions. It had to be reseeded in June 1980. A straw mulch was used in two experimental units but did not assist its establishment. When the mixture failed to germinate in 1981, it was replaced by common vetch. This plant was chosen for its hardiness, competitiveness and large seed which allowed it to be drilled, thereby being placed deeper in the soil and better able to exploit whatever moisture was available. It was reseeded in the intercrop plots with a 'Planting Junior' but

Table 6. Field practices on corn plots, Franklin gravelly loamy sand

		Year		
		1980	1981	1982
Site preparation		05/05	16/04-05/05	02/05
Seeding date		12/05	05/05+07/05	05/05
rate (seeds/ha)		54,400	59,000	60,000
Fertilizer (kg/ha) ($N-P_2O_5-K_2O$)	side dress	28-55-82	44-60-80*	44-64-80
	top dress	105-0-0	2 50-0-0	as 1981
			3 100-0-0	
	total	133-55-82	1 44-60-80	44-64-80
			2 94-60-80	94-64-80
			3 144-60-80	144-60-80
Harvest date	sub-sample	03/09	17/09	31/08
	total	28/09	29/09	08/10

* Block 1 was fertilized at 25-50-75 kg/ha $N-P_2O_5-K_2O$.

Table 7. Field practices on green manure and intercrop plots
Franklin gravelly loamy sand

	Year		
	1980	1981	1982
		Buckwheat	
Seeding date	05/06	03/06	08/06
Seeding rate (kg/ha)	94.0	227.0	227.0
Fertilizer (N-P_2O_5-K_2O kg/ha)	33-33-33	40-40-40	34-34-34
Incorporation date	10/08	11/07	20/07
		Plowdown or vetch	
Seeding date	05/05+17/06	05/05-03/06	05/05
Seeding rate (kg/ha)	20.2	unknown	183.0
Fertilizer (N-P_2O_5-K_2O kg/ha)	17-67-67	13-80-106	7-44-58
Incorporation date	30/04/81	13/08	20/07
		Corn/Plowdown or corn/vetch	
Seeding date			
corn	12/05	05/05+07/05	05/05
Plowdown	05/05+17/06	05/05	
vetch		03/06	05/05
Seeding rate			
corn (seeds/ha)	54,400	59,000	60,000
Plowdown (kg/ha)	20.2	unknown	
vetch (kg/ha)		10.1	183.0
Fertilizer (N-P_2O_5-K_2O kg/ha)	150-122-149	144-60-80	7-44-58

did not establish well, even with a second seeding, due to strong competition from the already established corn (Warwick w-777). As a result, the seeding rate was increased in 1982 and the time of planting changed to give it a better chance to establish. The fertilizer rate in the intercrop plot was lowered considerably to accommodate the associated fertility experiments.

Fertilizer rates were set below recommendations except for N application to buckwheat which was actually higher than recommended because of confusion about the variety's maturation period. Block 1 was incorrectly ferilized at 25-50-75 kg/ha in 1981. Treatment H was randomly split into three sub-plot units and received different fertilizer rates (Table 6). The rate applied to sub-plot 2 corresponded to the rates of the main-plot units. Treatments A, B, D, G, and H were split in 1982. Lime was applied in 1981 at 3.3 t/ha $CaCO_3$ equivalent as it was felt that the pH was a limiting factor in 'Plowdown' development. The higher pH did not assist its growth.

The buckwheat (Fagopyron esculentum L.) seeding rate was increased in 1981 to ensure that seeding rate was not a limiting factor in stand density. Buckwheat, 'Plowdown', and vetch were incorporated by discing in all three years. Two passes had to be made on several occasions to more completely incorporate the material. Weeds were controlled by cultivation, though atrazine was used in 1981 at 2.5 kg active ingredient/ha. This was not effective but the rate was not increased due to the possibility of having residual effects.

Corn yield was determined on a per-plant basis and multiplied by the stand density. Biomass produced by green manures was determined on an area basis. All sampling was done in three random locations of each experimental unit. The site was not plowed in the fall of 1980, but in late April of 1981. Fall plowing was done following the 1981 and 1982 growing seasons.

LABORATORY EXPERIMENT

A laboratory experiment was conducted on the Franklin soil to evaluate whether aggregation would occur in response to green manure in a more controlled environment than the field. The experiment was a 2x3x6 factorial experiment with 2 replicates. Two green manures were used, buckwheat and common vetch, as in the field experiments, and were applied to the soil in three different ways: finely chopped and thoroughly mixed with the soil, simulated plowing (achieved by sandwiching a layer of plant material between soil layers), and simulated disc incorporation (achieved by mixing coarsely chopped plant material with soil in the top third of the cup). Buckwheat and vetch were added to the soil at the rate of 4.5 t/ha. Six aggregating forces were applied: three different moisture contents, freezing and thawing, wetting and drying, and compaction (Table 8).

The experiment was of 21 days duration on a growth bench with a controlled daytime environment of approximately 12 hours sunlight, $25^{o}C$ and 70% humidity. Night temperature was $15^{o}C$ with the same humidity. Covers were removed from the incubation cups every second day for a few minutes to maintain aerobic conditions except treatment 6 which was not covered to allow moisture to evaporate. All samples were air dried prior to aggregate-distribution analysis.

Table 8. Details of lab experiment, Franklin gravelly loamy sand

Treatment	Aggregating force	Moisture	Bulk density (Mg/m^3)	Remarks
1	field capacity	-0.1 bar	1.22	
2	freezing and thawing	-0.1 bar	1.22	48h at -2^{o}C then 48 h at 23^{o}C. 2 cycles
3	optimal moisture	-0.87 bar	1.22	
4	moisture stress	-5.0 bar	1.22	
5	compaction	-0.1 bar	1.40	
6	wetting and drying	variable	1.22	wetting to -0.1 bar then 5 days drying

Table 9. Sampling information, Bearbrook clay

Parameter	Year	Sampling time	Sampling depth	Sampling location[1]
Bulk density +	80	pl/aug/bh	each 5 cm to 20 cm	ncomp
Gravimetric	81	bc/aug/ph	each 5 cm to 20 cm	ncomp
water content	82	bpl/aug/ph	each 5 cm to 20 cm	comp+ncomp
Aggregation	80	pl/aug	0-10, 10-20 cm	ncomp
	81	aug/ph	0-10, 10-20 cm	ncomp
	82	bpl/ph	0-10, 10-20 cm	ncomp
Water retention	80	bh	0-10 cm	ncomp
	81	aug	0-10, 10-20 cm	ncomp
	82	bpl/ph	0-10, 10-20 cm	ncomp
Water flow	80	bh	0-10 cm	ncomp
	81	-	-	-
	82	bc/ph	0-15 cm	comp+ncomp[2]
pH, Ca, O.C.	80	h	0-20 cm	corn row
	81	ph	0-10, 10-20 cm	interrow
	82	bpl/aug/ph	0-10, 10-20 cm	interrow
Tissue	80	not sampled	-	-
	81	incorporation	-	-
	82	incorporation	-	-

Legend

bpl	- pre-planting	aug	- mid-August	ph	- post-harvest
pl	- planting	bh	- pre-harvest	comp	- trafficked rows
bc	- pre-cultivation	h	- harvest	ncomp	- non-trafficked rows

[1] Sampling within 20 cm radius of corn row in corn plots except where noted.

[2] Cylinders placed directly over corn row in corn plots for the post-harvest sampling period.

Table 10. Sampling information, Franklin gravelly loamy sand

Parameter	Year	Sampling time	Sampling depth	Sampling location[1]
Bulk density +	80	bc/aug	each 5 cm to 20 cm	ncomp
Gravimetric	81	bc/jul/ph	each 5 cm to 20 cm	comp[2]+ncomp
water content	82	bpl/ph	each 5 cm to 20 cm	comp+ncomp
Aggregation	80	bc/aug/ph	0-10, 10-20 cm	comp+ncomp
	81	bc/jul/bh	0-10, 10-20 cm	ncomp
	82	bpl/ph	0-10, 10-20 cm	comp+ncomp
Water retention	80	ph	0-20 cm	comp
	81	aug	0-20 cm	ncomp
	82	bpl/ph	0-20 cm	comp+ncomp
Hydraulic conductivity	80	ph	0-20 cm	comp
	81	aug	0-20 cm	ncomp
	82	bpl/ph	0-20 cm	comp+ncomp
pH, Ca, O.C.	80	h	0-20 cm	corn row
	81	bh	0-10, 10-20 cm	interrow
	82	ph	0-10, 10-20 cm	interrow
Tissue	80	incorporation	-	-
	81	incorporation	-	-
	82	incorporation	-	-

Legend

bpl - pre-planting	aug - mid-August	ph - post-harvest
bc - pre-cultivation	bh - pre-harvest	comp - trafficked rows
jul - July	h - harvest	ncomp - non-trafficked rows

[1] Sampling within 20 cm radius of corn row in corn plots except where noted.

[2] All sampling in the post-harvest sampling period was done in compacted soil.

PHYSICAL ANALYSES

Tables 9 and 10 contain the times and locations of sampling for all parameters. The sub-plot units were only sampled for aggregate distribution and stability analysis as these are the only parameters likely to be affected by N fertilizer rate (Ram and Zwerman, 1960).

Coarse fragment and particle-size analysis

The quantity of coarse fragments in the plow layer (0-20 cm) of the Franklin soil was determined by hand sieving a soil volume 100 times greater than the volume of the largest fragment (Avery, 1974). Coarse-fragment volumes were determined by displacement in water (Smith and Thomasson, 1974). Having determined the density and gravimetric proportion of coarse fragments in the Franklin soil, the density of the soil alone ($<$2.00 mm) could be calculated for any given total soil bulk density using:

$$\rho b = \rho s \; \rho t R / \rho s - \rho t(1-R)$$

where R = ratio of $<$2.00 mm fraction to total sample weight on an air-dry basis, ρb = bulk density of $<$2.00 mm fraction, ρs = coarse fragment density, and ρt = total bulk density (Mehuys et al., 1975).

Particle-size distribution was determined by the hydrometer method (Day, 1965).

Bulk density

Bulk-density measurements were made by radiation-scattering using a surface moisture-density gauge, Troxler model 2401 (1980 and 1981) and 3401 (1982). The instrument determined wet density which was corrected to an oven-dry basis from a gravimetric-moisture determination.

Aggregate distribution and stability

Aggregate distribution was determined by dry-sieve analysis using flat sieves of 4.75, 2.00, 1.00, and 0.25 mm openings, respectively, on a mechanical shaker at 276 revolutions per minute. All samples were passed through an 8-mm sieve, using a rubber hammer, prior to shaking. Franklin gravelly loamy sand samples were corrected for sand content using the method of Kemper (1965). The mean weight diameter (MWD) (Van Bavel, 1949) and the percent aggregated material of total non-sand fractions present (Kemper, 1965) were used as indices, but the MWD proved to be so variable and have such low values that the index outlined by Kemper was deemed more suitable. All 1980 samples were oven dried; 1981 and 1982 samples were air dried. Because oven drying can increase the stability in water of aggregates, the 1980 Bearbrook samples were sprayed with approximately 1 ml of water and allowed to air dry in an attempt to reverse this effect (Nijhawan and Olmstead, 1947). With the Bearbrook soil, an index developed in Poland by Dobrzanski et al. (1975) was used to evaluate aggregate distribution. The index attempts to measure agriculturally-valuable aggregates by assigning a weight value to each aggregate-size range. Several authors have indicated that aggregates between 1 and 5 mm are the most important for plant growth (Kononova, 1966; Allison, 1973). Table 11 contains a comparison of weight values used in the Polish study and in this study. The index, AI, is calculated by the equation:

$$AI = \Sigma P_i Q_i$$

where P_i = content of aggregate fractions in percent, and Q_i = weight value assigned to an aggregate fraction (i).

Table 11. Aggregate weight values

Dobrzanski et al. (1975)								
Aggregate size (mm)	>10	10-7	7-5	5-3	3-1	1-0.5	0.5-0.25	<0.25
Weight value (Q)	0	1	3	8	10	5	3	0

MacRae						
Aggregate size (mm)	>8	8-4.75	4.75-2	2-1	1-0.25	<0.25
Weight value (Q)	0	3	8.5	9.5	4	0

Aggregate distribution in water was determined, by wet sieving, on the Bearbrook soil only. (As a primary physical problem on the Franklin soil is wind erosion during tractor operations, the dry-sieve analysis was thought to be most suitable for evaluating aggregation status (Chepil, 1951)). The samples were sieved in water for 2 minutes at a rate of 42 strokes per minute. The sieves were displaced vertically 3.3 cm. The same index used for dry-aggregate distribution was used to evaluate the wet-aggregate distribution. The percentage wet value/dry value was used as an indicator of the resistance of the aggregates to disintegration in water (refered to hereinafter as stability). Three indices were used to evaluate the effect of N fertilizer rates on wet-aggregate distribution: percentage of aggregates between 0.25 and 4.75 mm in size (WA), percentage of aggregates between 0.25 and 2.00 mm in size (SA), and percentage of aggregates between 2.00 and 8.00 mm in size (LA).

Moisture retention

Moisture retention was determined on pressure plate and pressure membrane apparati. Undisturbed Bearbrook samples were used for low-pressure determinations. At -15 bars, equilibrium could not be attained consistently with undisturbed samples, so determinations were made on disturbed, oven-dried samples, crushed to pass a 2-mm sieve. In 1980, cores of approximately 8 cm height by 8 cm diameter were used. In 1981 and 1982, smaller cores of 5 cm by 5 cm were used to speed up equilibration time.

Disturbed samples were used for analysis of the Franklin soil as cores could not be driven into the ground because of the quantity of coarse fragments. All coarse fragments were removed from the sample. Cores 5 cm in diamenter and 2 cm high were packed to the field density of the fine-earth fraction (<2 mm) alone. Three sub-samples per experimental unit were prepared except for the 1980 samples which were not sub-sampled. At equilibrium, the moisture content of the samples was determined gravimetrically. Moisture retention of the total soil was estimated using:

$$M_w = M_f/(1+R)$$

where M_w = retentivity of whole soil, M_f = retentivity of fine soil (<2.00 mm), and R = ratio of weight of coarse fragments to soil (Richards, 1965).

Water flow

Saturated hydraulic conductivity (Ksat) was determined by the falling-head method with Ksat being mathematically determined by regression, using a computer programme developed in the Dept. of Agricultural Engineering, McGill University. Undisturbed cores, approximately 8 cm high by 8 cm diameter, were used with the Bearbrook soil. For the Franklin soil, disturbed samples, with coarse fragments removed, and packed to field density in 2-cm intervals, were used. The procedure was run thrice per sample.

The falling-head method proved to be unsatisfactory on the Bearbrook soil as it was too difficult to obtain a good undisturbed sample and worm channels were not avoidable. As a result, a modified infiltration procedure was developed for the Bearbrook site. Rings of 26 cm diameter and 20 cm high were placed in the soil to a depth of 15 cm. Water was added to the soil surface to produce a 2-cm head at time, t=0. The time necessary for the water to infiltrate was recorded. After 1 minute the procedure was repeated. If it took longer than 20 minutes for the water to infiltrate, the test was halted and the soil considered to have sealed. Up to 12 cm of water were added to the soil surface.

CHEMICAL ANALYSES

Soil samples were obtained from main and sub-plot units, air dried and ground to less than 1 mm. Soil organic carbon was determined by the Walkley-Black method (Allison, 1965). Soil pH was determined with a glass-calomel electrode (1:3 soil to water ratio by volume). Soil extractable phosphorus was determined using the Bray 2 method (Bray and Kurtz, 1945). Soil potassium and calcium were extracted using 1N ammonium acetate at pH 7 (Chapman, 1965) and determined by flame photometry.

Plant tissue was dried at 70°C and ground through a 20-mesh sieve. It was digested with a sulfuric-peroxide digestion (Miller and Miller, 1948). NH_4-N was determined following the alkaline phenol hypochlorite method described by O'Brien and Fiore (1962).

STATISTICAL ANALYSES

Standard analyses of variance (Steel and Torrie, 1980) were carried out on all data except water-flow experiments on the Bearbrook soil which were analyzed by Friedman's 2-way analysis of variance (Siegel, 1956). The stepwise multiple linear-regression procedure was used to evaluate the relationship between yield and various physical-property parameters using the maximum R^2 option for determining the best model. Standard multiple linear correlations were determined for all independent variables in the model. Physical-parameter data from the final sampling period were used in the correlations and regression models.

RESULTS AND DISCUSSION

BEARBROOK CLAY

Background data

Monthly rainfall data are presented in Table 12. The fall of 1980 and spring of 1981 were very wet, but 1982 was a dry growing season, particularly May, September and October.

Incorporated material is characterized in Table 13 by total biomass produced and % N of the tissue. The green manures were not sampled prior to incorporation in 1980. From visual observation, clover-stand densities in that year were the lowest of the three years of the study. A negligible quantity of green-manure dry matter was produced in the intercrop treatment (treatment D) in 1980 and 1981. Inappropriate selection of intercrop species in 1980 and a lack of information on compatible seeding rates and dates were the causes of this poor performance. Because barley stubble and weeds, with low tissue-N levels, were included in the collected samples, tissue nitrogen values were generally low. This was particularly the case for sweet clover (treatments F and H) which did not establish as well as the red clover.

Soil organic carbon, pH, and calcium

There were no significant treatment effects on levels of soil organic carbon in the main-plot units in any sampling period. Over the three years, the mean values from sampling periods first increased quite dramatically to a high of 3.06% at post-harvest, 1981 (Fig. 1) and then decreased gradually during 1982. As indicated by the standard deviations, this decline was not

Table 12. Total rainfall
Bearbrook clay

	Year		
Month	1980	1981	1982[1]
	cm		
May	nd	9.7	5.9
June	2.8 (5)[2]	13.2	12.1
July	14.9	8.1	5.5
August	5.8	11.0	12.9
September	13.8	10.8 (24)	7.1
October	7.5	nd	3.8
Total	44.8	52.8	47.3

[1] Data from Ministère de l'environnement du Québec.

[2] Number in brackets is the day of the month recording began or ended.

nd Not determined.

Table 13. Characterization of green manures used on Bearbrook clay

	Treatment						
Measurement	B	C	D	E	F	G	H
1980 Dry matter (t/ha)		nd	neg	nd			
% N		nd	nd	nd			
1981 Dry matter (t/ha)			neg			4.75[1]	3.59[1]
% N			nd			1.69[3]	1.21[3]
1982 Dry matter (t/ha)	3.95[1]		2.38[1,2]		3.53[1]		
% N	1.94[3]		1.57[2,3]		1.51[3]		

nd Not determined

neg Negligible biomass produced

[1] Top dry matter multiplied by root:shoot ratio.

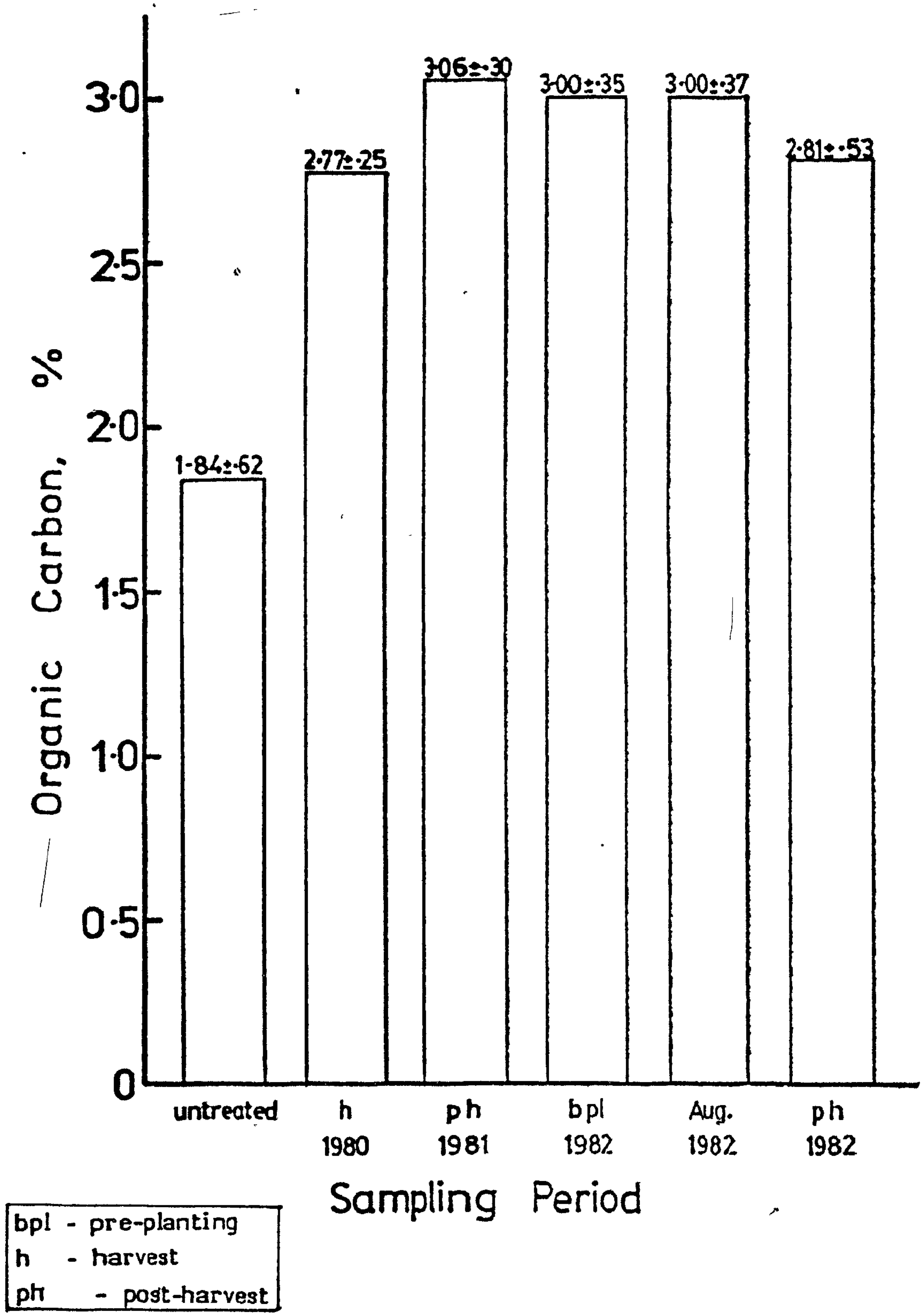
red clover/barley	1:3.26	(determined 1981)
sweet clover/barley	1:2.60	(determined 1981)
vetch	1:9.67	(determined 1982)

[2] Does not include corn stubble.

[3] Determined by multipling % N of tops and roots respectivley by the root:shoot ratio, % N values for roots determined in 1982.

Figure 1 Soil Organic Carbon, Sampling Period Means

1980-1982, Bearbrook Clay



significant. The final level was considerably higher than levels recorded prior to the experiment. This is largely a function of increased organic carbon from 10-20 cm. Prior to commencement of the experiment, organic-carbon levels were only 1.24$\pm$0.65% (Table 1).

There were no significant effects due to treatment on pH and calcium in main-plot units in any sampling period of the experiment. Effects in sub-plot units are presented below in association with the effect of N fertilizer rates on aggregation.

Aggregation

There was a general improvement in the distribution value of dry aggregates (AI) over the course of the experiment, with some seasonal variability apparent (Fig. 2). Samples collected in August of 1980 and 1981 had the highest values as these were the first sampling periods to follow cultivation for weed control. By post-harvest, the index indicated a less favourable environment for plant growth than earlier in the growing season. This effect likely resulted from soil settling, the effects of rainfall, and root pressures from growing plants. No significant differences between treatments were apparent until the final sampling period at post-harvest, 1982. At this time, there was a significant effect at $p \leq 0.05$. Although the results of the means test are not clear cut, it is apparent that plots cropped to green manures in 1980 and 1981 had a more favourable dry-aggregate distribution. Treatment G (red clover in 1981) was significantly different ($p \leq 0.05$) from treatments B (red clover in 1982), D (intercrop), and F (sweet clover in 1982) (Fig. 3).

Figure 2 Dry and Wet-Aggregate Distribution and Stability, Sampling Period Means

1980-1982, Bearbrook Clay

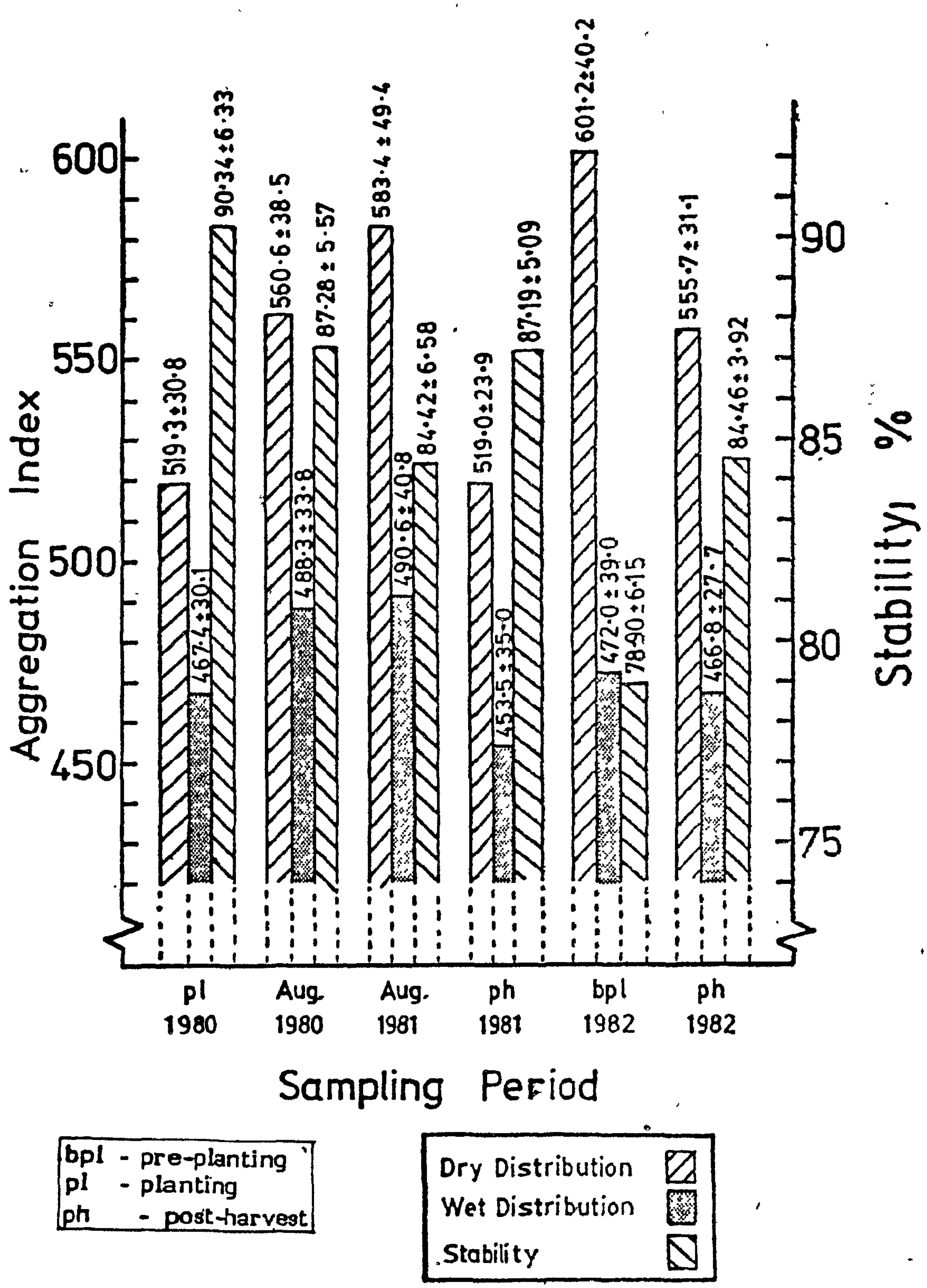
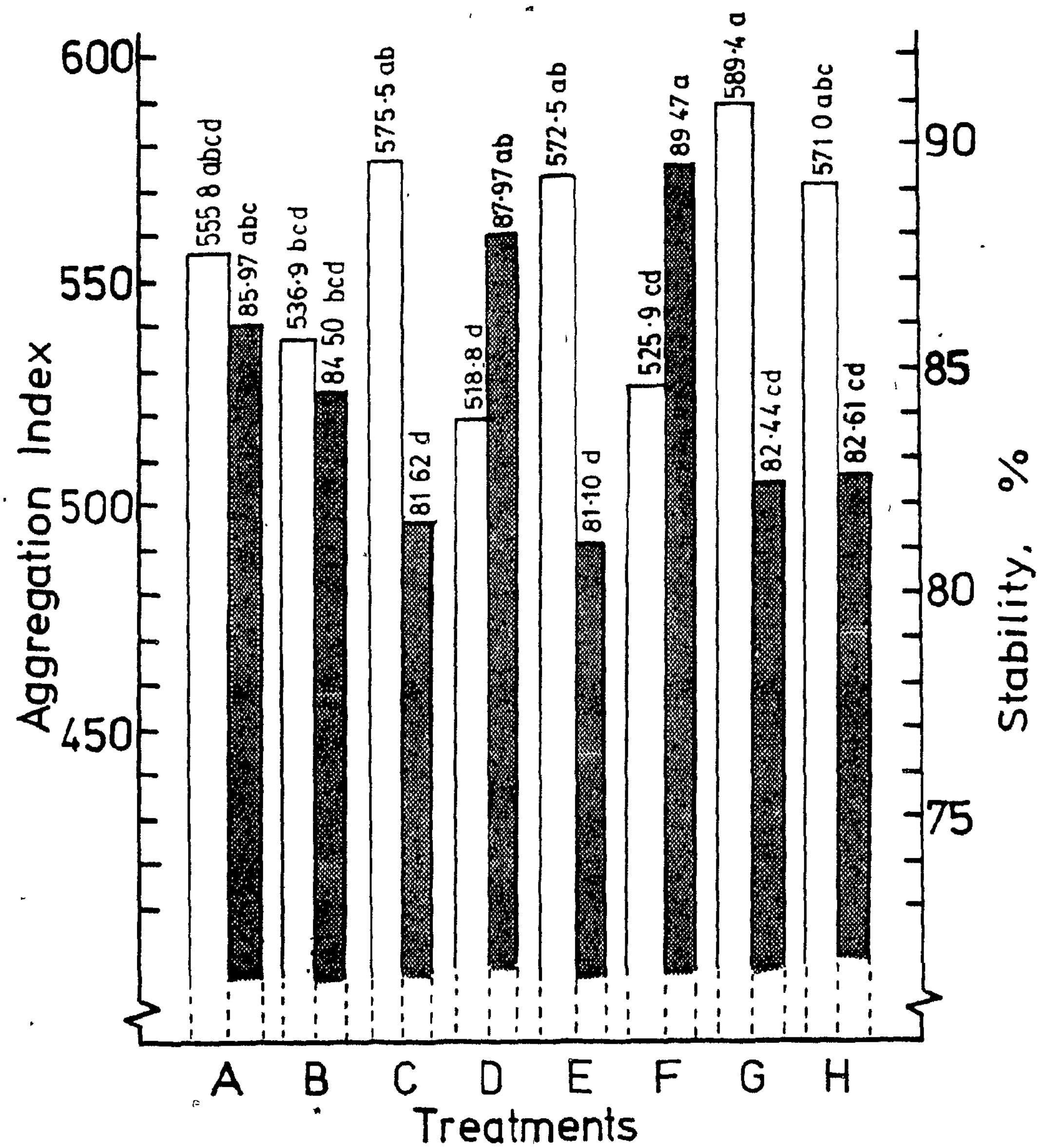


Figure 3 Dry-Aggregate Distribution and Stability, Treatment Means

— Post-Harvest 1982, Bearbrook Clay



Means with the same letter are not significantly different ($p \leq 0{\cdot}05$) by the Waller-Duncan K-ratio test

Stability ■
Dry-Aggregate Distribution □

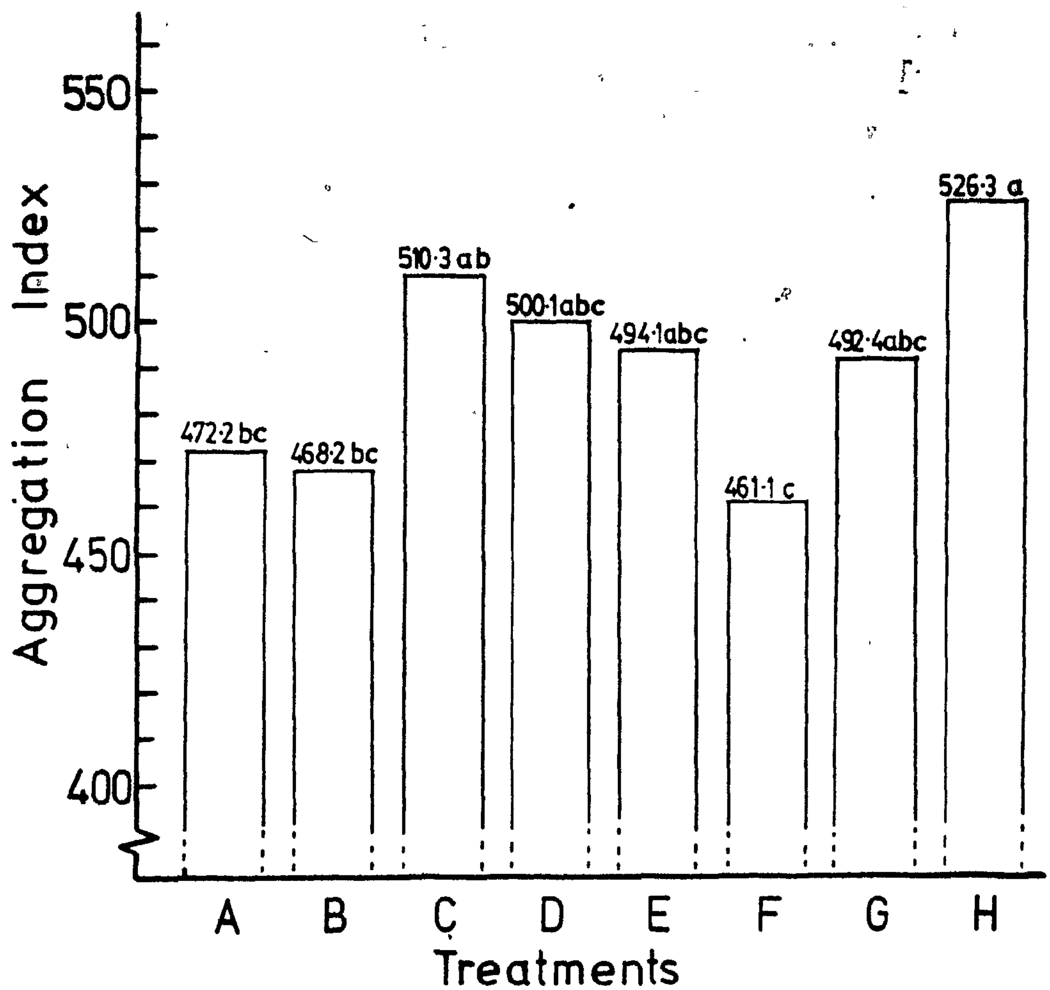
Wet-aggregate distribution remained quite constant over the three years (Fig. 2). There were significant differences between treatments in August, 1981 ($p \leq 0.05$) and pre-planting, 1982 ($p \leq 0.01$). In August, 1981, treatment H (sweet clover in 1981) was significantly different from treatments A, B, and F (Fig. 4). This effect did not persist through to the post-harvest period. By pre-planting, 1982, the beneficial effects of the clovers, apparent the previous August, had disappeared (Fig. 5). The monoculture treatment (treatment A), had a significantly higher wet-aggregate-distribution value ($p \leq 0.05$) than treatments C, E (both clovers in 1980), and H. Only treatment G (red clover in 1981) of the green-manure treatments was not significantly different from treatment A. This effect did not persist to the next sampling period.

There was a steady decline in the ability of aggregates to resist disintegration in water. This decline in stability was due to cultivation. Other work done in Québec (Martel and MacKenzie, 1980; Millette et al., 1980) has also found cultivation to produce this effect. The seasonal fluctuation of stability was opposite to that of dry-aggregate distribution. The lowest values were recorded after land preparation or cultivation (Fig. 2). Significant treatment effects occurred only at pre-planting ($p \leq 0.05$) and at post-harvest, 1982 ($p \leq 0.01$). In both sampling periods, plots not cropped to green manures, or having insignificant growth of green manure, in 1980 or 1981 had the highest stablility (Fig. 5 and 3). At pre-planting, treatments A and F had significantly higher stability than treatments E and H. At post-harvest, treatments D and F had significantly higher values than treatments C, E, G, and H.

As mentionned in the opening paragraph of the <u>Materials and Methods</u>, this site was in pasture for at least five years prior to the commencement of

Figure 4 Wet-Aggregate Distribution, Treatment Means

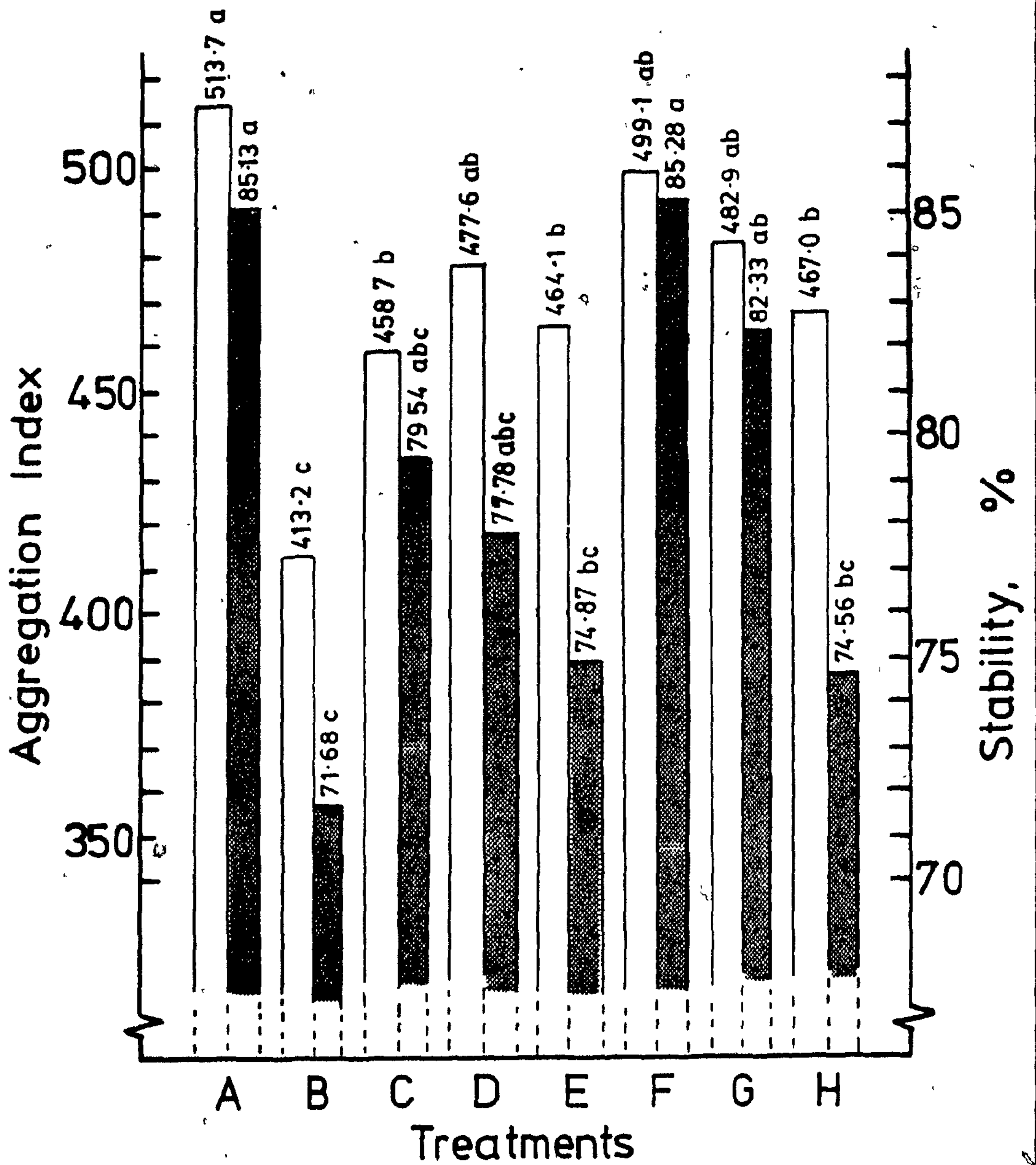
August 1981, Bearbrook Clay



Means with the same letter are not significantly different ($p \leq 0{\cdot}05$) by the Waller-Duncan K-ratio test.

Figure 5 Wet-Aggregate Distribution and Stability, Treatment Means

Pre-Planting 1982, Bearbrook Clay



Means with the same letter are not significantly different ($p \leq 0{\cdot}05$) by the Waller-Duncan K-ratio test.

Stability ■

Wet-Aggregate Distribution □

the experiment. The structure of this soil is inherently poor. The dry-aggregate distribution index of the uncultivated soil was in the low 500's (Table 1) with aggregates of 4.75-8.00 mm in diameter the most abundant. The results indicate that mechanical manipulation of the soil improved the dry-aggregate distribution by breaking down the large aggregates. The effect of cultivation for weed control was likely a primary factor in effecting this result. This is demonstrated by the values produced in the sampling period following cultivation in 1980 and 1981 as well as by the depth effects from each sampling period (Table 14). By August 1981, the depth means for dry AI showed significant differences ($p \leq 0.05$). From 0-10 cm, the average depth to which the cultivator penetrated, a more favourable environment for plant growth existed than from 10-20 cm.

It is evident that treatments which had green manures in 1980 and 1981, particularly treatment G, had more favourable dry AI values. It may be that more coarse, inert organic material was present in this treatment. After mechanical breakdown of the aggregates, this material would keep aggregates small by reducing exterior forces between them. Small aggregates in plots that were not cropped to green manures in 1980 and 1981 could have been bound into larger aggregates by these physical forces in the absence of this coarse organic material. As the quantity of coarse organic material in each treatment was not determined, this explanation of the results cannot be proven.

Although the dry AI value improved, the wet AI value did not, indicating that the dry aggregates produced were not water stable. There was no increase in the number of aggregates stabilized by organic matter. In fact, results from the pre-planting, 1982 sampling period suggest that plots cropped to green manures had fewer aggregates stable in water than those that

Table 14. Depth means of aggregate analyses for each sampling period, 1980-2
Bearbrook clay

		Aggregation index		
Sampling	Depth (cm)	Dry AI	Wet AI	Stability (%)
pl 80	10	515.0	459.9	89.63
	20	523.5	474.9	91.05
aug 80	10	569.8	493.3	85.05b
	20	551.4	483.2	89.52a
aug 81	10	610.0a	491.1	80.70b
	20	556.8b	490.1	88.14a
ph 81	10	536.0a	462.4	85.81
	20	502.1b	444.6	88.57
bpl 82	10	634.1a	481.2	76.14b
	20	568.3b	462.9	81.65a
ph 82	10	605.5a	488.6a	80.98b
	20	505.9b	445.0b	87.94a

Means with the same letter within aggregate distribution-depth-sampling combinations are not significantly different ($p \leq 0.05$) by Duncan's new multiple range test.

Legend

bpl - pre-planting   pl - planting   ph - post-harvest were not. This is possible if the act of incorporation caused the "priming" of native organic carbon and a reduction in total soil organic-carbon levels (Broadbent and Norman, 1947; Allison, 1973) although the results of the soil organic-carbon analysis do not support this conclusion. The stability data show, as well, that plots that were not in green manures in 1980 or 1981 had more stable aggregates though this may be as much a function of arithmetic manipulation as anything else, for the results are basically the inverse of the dry AI results. Differences in aggregation between treatments cannot be explained by the soil organic-carbon, pH, or calcium results. The failure of soil organic-carbon results to demonstrate effects that might explain the aggregation results could be because the Walkley-Black procedure does not differentiate between the various components of soil organic matter (Greenland, 1965).

Effect of N fertilizer rates on aggregation

Fertilizer rates affected significantly the distribution of wet aggregates at pre-planting, 1982 ($p \leq 0.01$) and there was a significant interaction of treatment with N fertilizer rates at post-harvest, 1982 ($p \leq 0.05$) (Table 15). In the pre-planting sampling period, the percentage of aggregates 0.25-4.75 mm in size (WA) was significantly lower ($p \leq 0.05$) at 0 kg N/ha than at 50, 100, or 150 kg N/ha. The percentage of aggregates 0.25-2.00 mm in size (SA) was significantly lower ($p \leq 0.05$) at 0 kg N/ha than at 100 or 150 kg N/ha. The percentage of large aggregates (LA), 4.75-8.00 mm in size, decreased as fertilizer rate increased though the differences were not significant at the 0.05 level of probability.

Table 15. Effect of N fertilizer rates on wet-aggregation indices, pre-planting and post-harvest, 1982
Bearbrook clay

	Sampling period					
	pre-planting 82 Wet-aggregation index			post-harvest 82 Wet-aggregation index		
N fertilizer (kg/ha)	WA	SA	LA	WA	SA	LA
0	55.53b	34.24b	48.42	51.46	30.31	53.59
50	60.92a	38.62ab	45.15	53.75	31.68	52.76
100	62.62a	40.71a	42.83	52.40	32.16	52.26
150	61.71a	41.19a	43.33	53.99	32.28	51.57

Means with the same letter within aggregate indices are not significantly different ($p \leq 0.05$) by the Waller-Duncan K-ratio test.

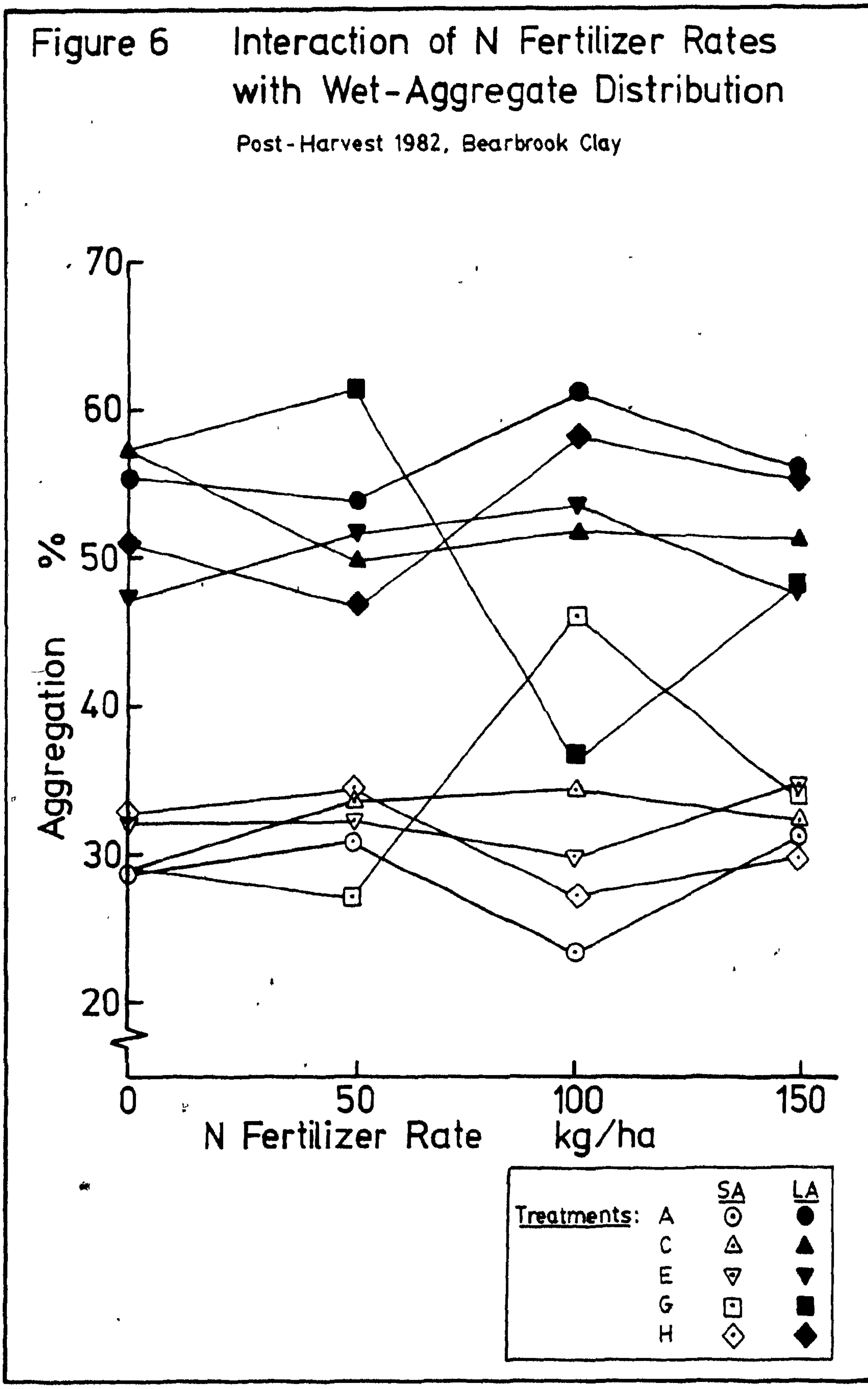


Figure 6 Interaction of N Fertilizer Rates with Wet-Aggregate Distribution
Post-Harvest 1982, Bearbrook Clay
70
60
50
40
30
20
Aggregation %
0
50
100
150
N Fertilizer Rate kg/ha
SA
LA
Treatments:
A
C
E
G
H

At post-harvest, 1982 an interaction between treatment and fertilizer rate occurred for two of the three above mentionned indices, namely SA and LA. The interaction is presented graphically in Fig. 6. The response of both indices to increased N fertilizer rates is visibly different for treatment G (red clover in 1981). The 100-kg/ha rate holds some special significance. Treatment E (red clover in 1980) had a slightly different response from treatments A (monoculture corn), C, and H (sweet clovers in 1980 and 1981 respectively). A similar trend for LA was apparent for treatment E from the pre-planting, 1982 sampling period, though the interaction of treatment with N fertilizer rate was only significant at the 0.10 level of probability (Fig. 7).

Ram and Zwerman (1960) found that as applications of N fertilizer increased, so did the proportion of small aggregates. They did not find any interaction between cover crops used in a cropping system and N fertilizer rate. They were unable to explain why N fertilizer rate significantly affected aggregate stability in water. It is likely that the effects reported here are a function of soil organic-matter levels, root action, and, possibly, the short-term decompostion products of the various organic additions. At pre-planting 1982, soil organic-carbon levels were significantly lower ($p \leq 0.05$) at 0 kg N/ha fertilizer than at 50, 100, or 150 kg N/ha (Table 16). The effect of N fertilizer rates on soil organic carbon was significant at the 0.01 level of probability in the analysis of variance. This low soil organic-carbon level at 0 kg N/ha was also likely a function of poor corn yields at low fertilizer rates in 1981. Results from the 1981 harvest (Table 16) show that fertilizer rate had a significant effect ($p \leq 0.01$) on yield and that yield at 0 and 50 kg N/ha was significantly different ($p \leq 0.05$) from yields obtained with 100 and 150 kg N/ha. The sub-plots with higher corn yield had more vigorous growth which

Table 16. Effect of N fertilizers on soil organic carbon (pre-planting 1982), and 1981 and 1982 corn yields
Bearbrook clay

N fertilizer (kg/ha)	Soil O.C. (%) bpl 82	Yield (t/ha) 1981	Yield (t/ha) 1982
0	2.73b	3.34b	2.82c*
50	2.93a	4.04b	5.01b
100	2.93a	6.78a	6.24ab
150	3.00a	7.35a	6.77a

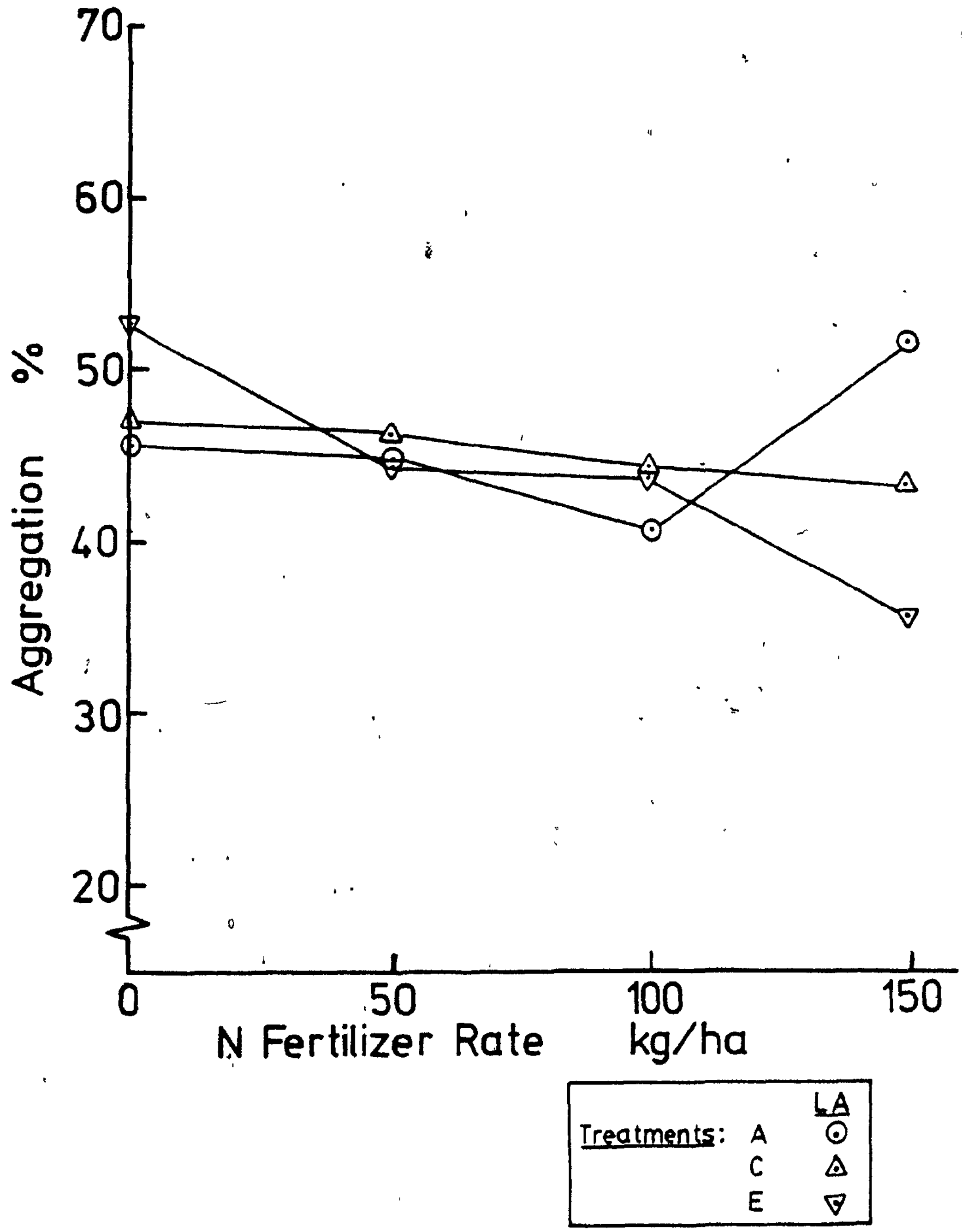
Means with the same letter are not significantly different ($p \leq 0.05$) by the Waller-Duncan K-ratio test (* Duncan's new multiple range test)

Table 17. Effect of treatment on soil organic carbon (post-harvest, 1982) and 1982 corn yield
Bearbrook clay

Treatment	Soil organic carbon (%)	Corn yield (t/ha)
A	2.92	5.12
C	2.93	4.20
E	2.47	5.99
G	3.16	7.22
H	2.85	5.01

Figure 7 Interaction of N Fertilizer Rates with Wet-Aggregate Distribution

Pre-Planting 1982, Bearbrook Clay



would mean a more vigorous root system. It is possible that root pressures caused the breakdown of large aggregates into smaller units.

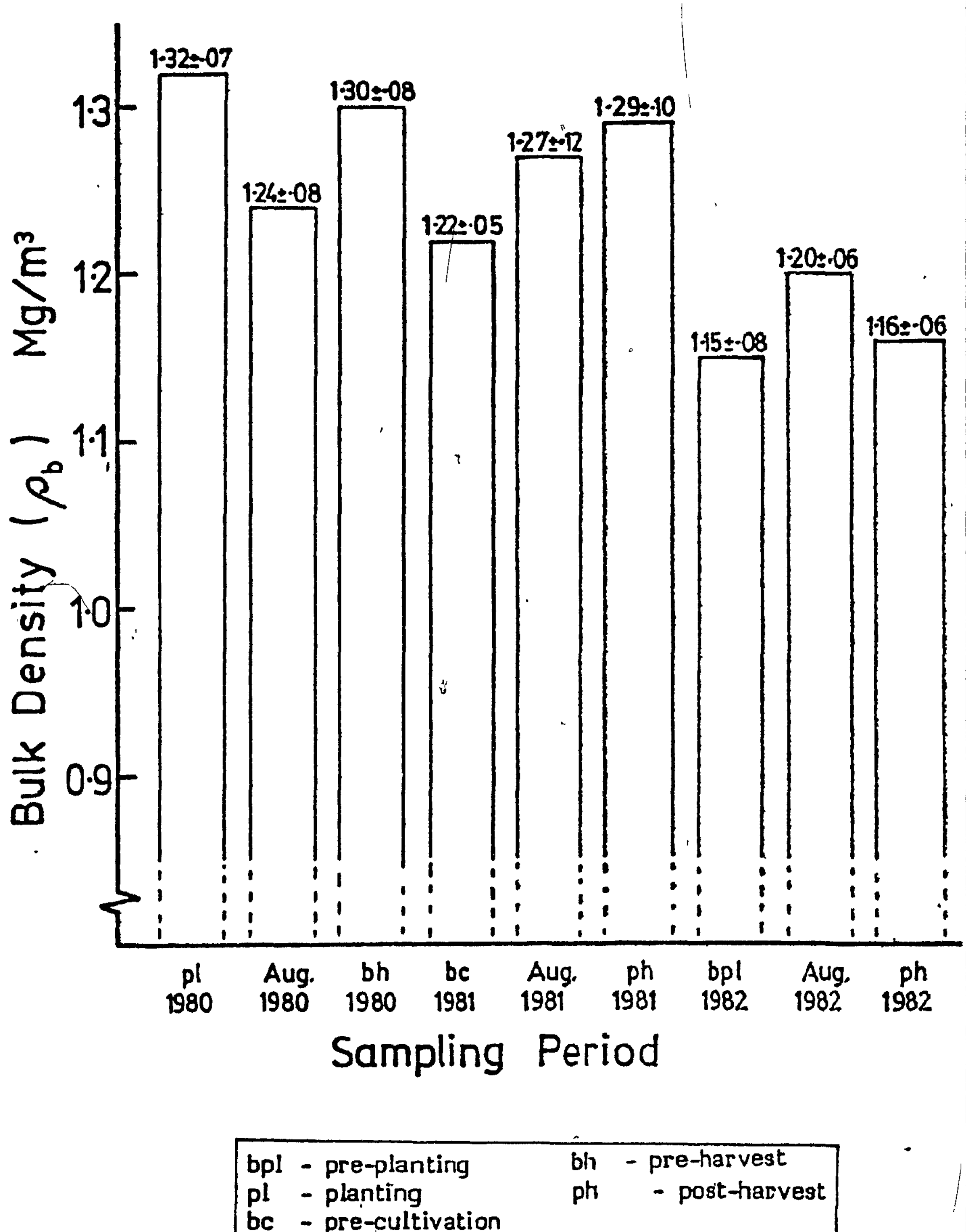
The interaction in the post-harvest sampling period is more difficult to explain. There were no significant effects ($p \leq 0.05$) of N fertilizer rate on soil organic carbon, soil calcium, or soil pH, but there were on corn yield ($p \leq 0.01$). Data in table 16 show that when no fertilizer was applied, low corn yields resulted. For two measured parameters there were significant effects at the 0.10 level of probability: the effect of treatment on soil organic carbon (sub-plot units only), and on corn yield in 1982, averaged over N fertilizer rates. Treatment G had the highest level of soil organic carbon and the highest corn yield (Table 17). This does not explain the reasons for the importance of the 100-kg-N/ha rate but does suggest that treatment G was the only treatment to retain conditions favourable to aggregate stability first evident in the pre-planting sampling period. It is also possible that the decomposition products of red clover were more suitable for the stabilization of a certain size of aggregate. This is suggested by the response of aggregates in treatment E to N fertilizer rates. In Table 17, soil organic-carbon levels are lower for treatment E than any other treatment, yet treatment E has a slightly more favourable response to N fertilizer rate than all other treatments in 1982, treatment G excepted.

Bulk density

There was an overall decrease in bulk density across all treatments (Fig. 8). From planting, 1980 to post-harvest, 1982, bulk density declined from 1.32 to 1.16 Mg/m^3. The seasonal variability corresponded with that of dry-aggregate distribution. As the dry-aggregate index decreased during the

Figure 8 Bulk Density, Sampling Period Means

1980-1982, Bearbrook Clay



growing season due to climatic and cropping factors, the bulk density increased. This seasonal variability occurred from 0-15 cm, which was the depth of heaviest mechanical disturbance. At 15-20 cm, bulk density was relatively unaffected (Fig. 9).

During the first two years of the experiment, a significant treatment effect occurred in only one sampling period, that of pre-cultivation, 1981. This effect was significant at $p \leq 0.05$. There was a significant interaction of treatment with depth ($p \leq 0.01$). An analysis of variance was performed at each depth. Only at 15-20 cm was there a significant treatment effect ($p \leq 0.01$), though the probability of a greater F statistic at 10-15 cm was 0.0581. The treatment means test ($p \leq 0.05$) is presented in Table 18. That the treatment effects occurred at the bottom of the plow layer is a result of the dilution of the soil matrix with a less dense material, the surface residues that were plowed under in the fall of 1980. All plots that were cropped to corn in 1980 did not have significantly different bulk densities except treatment B which was significantly different from all other treatments. Plots of treatment C, which were cropped to green manure and barley in 1980, produced significantly higher bulk densities than all treatments but A and H. Whether these differences are proportional to the amount of material incorporated is unknown.

There were significant treatment effects ($p \leq 0.05$) in the pre-planting, 1982 sampling period that were not caused by dilution. By the means test (Fig. 10), all treatments that had been successfully cropped to green manure to that point had significantly lower bulk densities than the monoculture corn (treatment A). Treatment B (red clover in 1982) was also significantly lower than treatment A, possibly a continuation of the trend that first appeared in the pre-planting sampling period the previous year.

Figure 9 Bulk Density at Each Depth, Sampling Period Means

1980-1982, Bearbrook Clay

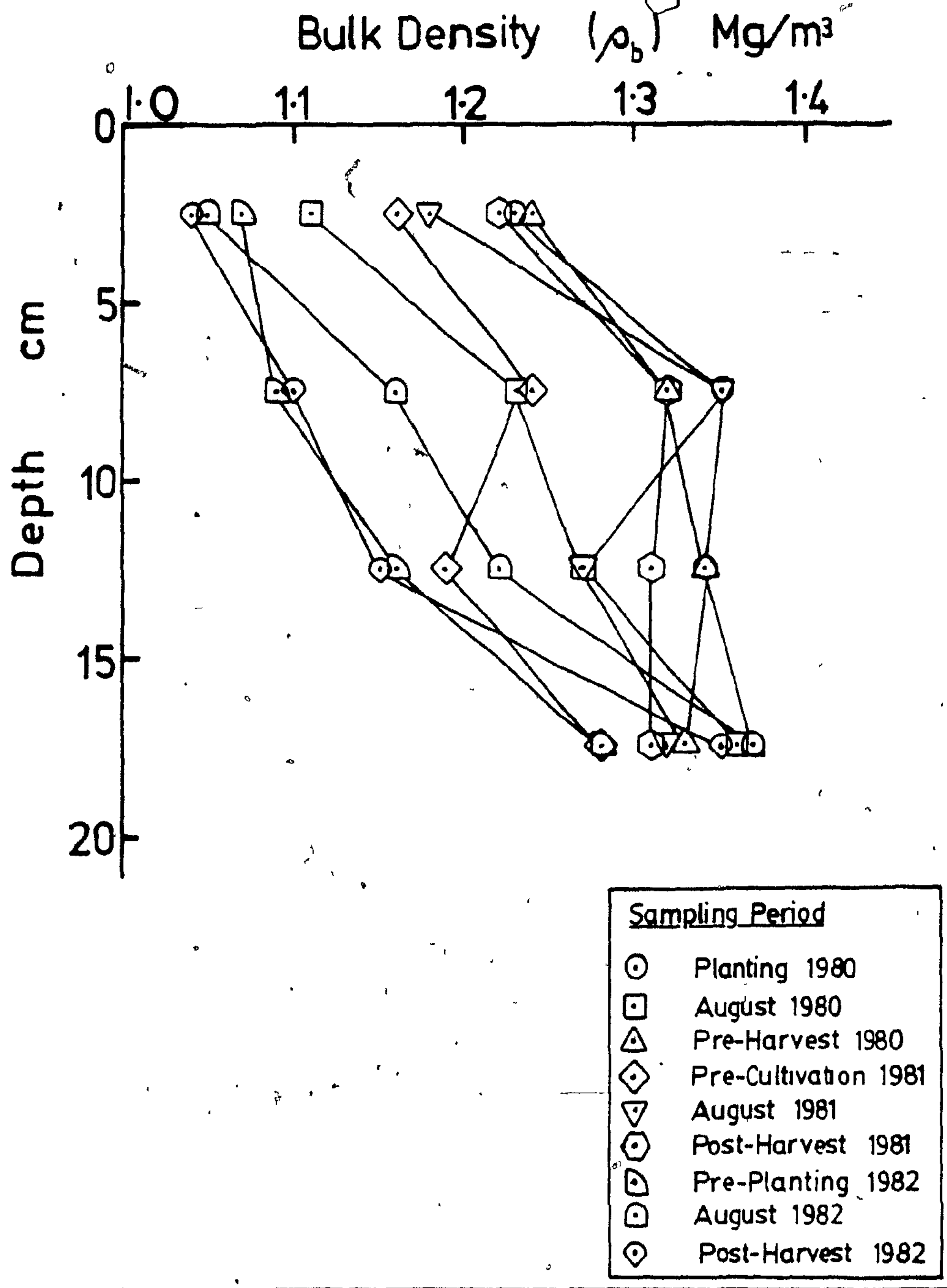


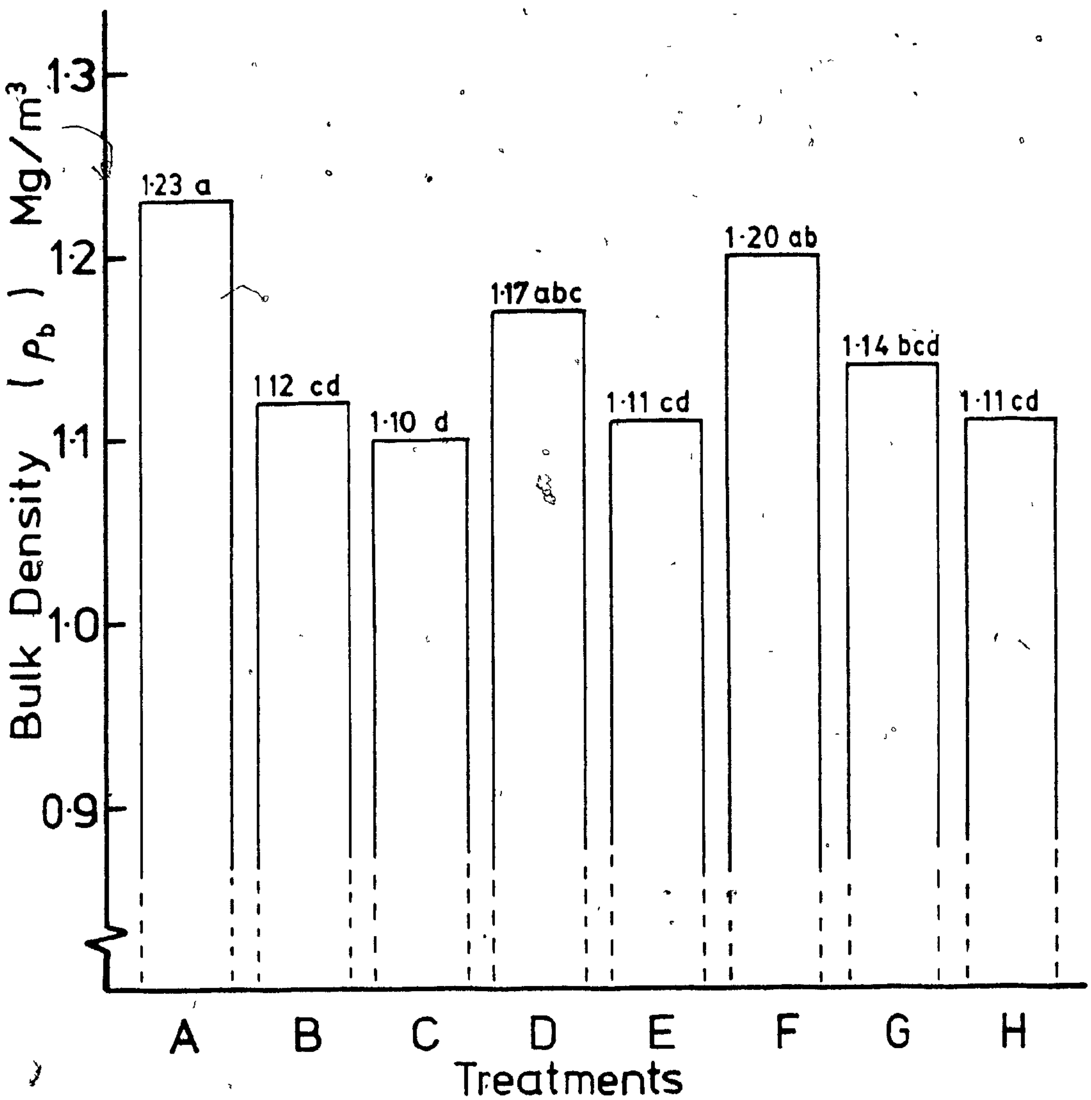
Table 18. Bulk-density means by treatment-depth combination, pre-cultivation, 1981
Bearbrook clay

	Bulk density			
	Depth (cm)			
Treatment	5	10	15	20
	Mg/m^3			
A	1.19	1.35	1.28	1.33ab
B	1.14	1.22	1.14	1.11d
C	1.18	1.23	1.17	1.39a
D	1.24	1.30	1.35	1.30b
E	1.10	1.21	1.18	1.21c
F	1.13	1.17	1.15	1.26bc
G	1.13	1.22	1.15	1.27bc
H	1.16	1.26	1.13	1.34ab

Means at each depth with the same letter are not significantly different ($p \leq 0.05$) by the Waller-Duncan K-ratio test

Figure 10 Bulk Density, Treatment Means

Pre-Planting 1982, Bearbrook Clay



Means with the same letter are not significantly different ($p \leq 0.05$) by the Waller-Duncan K-ratio test.

There was a significant interaction of treatment with depth ($p \leq 0.05$) in the August, 1982 sampling period. An analysis of variance by depth did not reveal the nature of the interaction though it suggested that the effect occurred from 5-15 cm. Figure 11 is a graphical representation of the effect. Treatments G and F showed a different response from the other treatments as the bulk density did not increase from 5-10 cm to 10-15 cm. As this is the interface of the zone of disturbance by the cultivator (0-10 cm), it is possible that the curves are expressing an induced mechanical effect, though its physical significance is not apparent.

An analysis of variance by depth of the data collected at post-harvest, 1982 (Table 19) reveals significant treatment effects at 0-5 cm ($p \leq 0.01$) and at 5-10 cm ($p \leq 0.05$). At 0-5 cm, treatments G and B were significantly different from treatments A, D, E, F, and H. At 5-10 cm, treatment G values were again the lowest, significantly different from values in treatments B and F (clover and barley in 1982). These plots were not mechanically disturbed after planting as were the other plots excluding those of treatment D. There were no significant treatment effects from 10-20 cm.

The bulk-density results are consistent with the dry-aggregation results. The lower bulk-density values were found in treatments that had green manure incorporated, particularly treatment G. Treatment G had the most favourable aggregation index for plant growth and had the most favourable interaction with N fertilizer rate in producing water-stable aggregates in the post-harvest sampling period of 1982. It appears that the beneficial effect of the green manure on bulk density may only persist for one growing season following incorporation. The positive effects of green manures in treatments C and E (green manures in 1980) did not persist through the 1982 growing season.

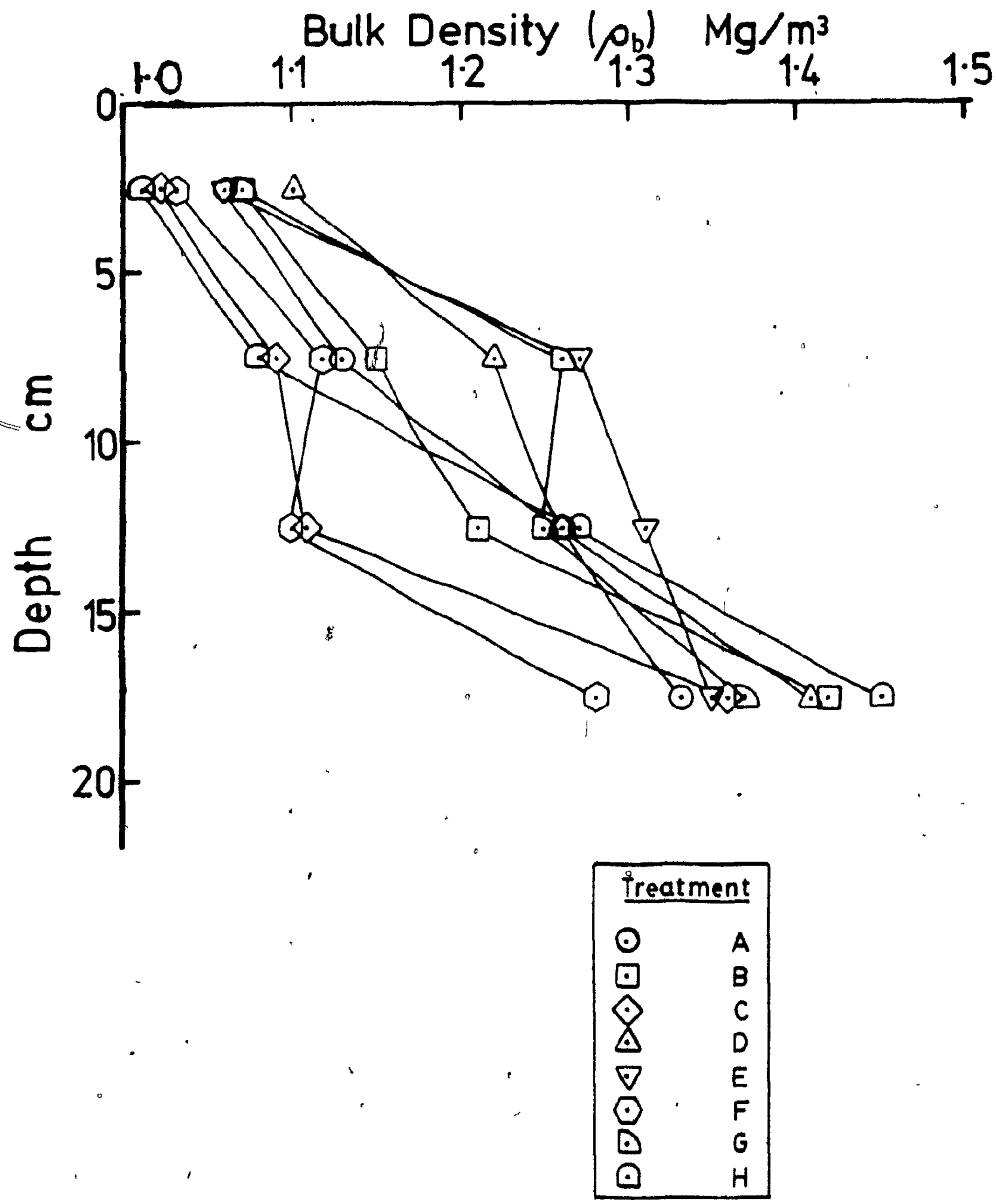
Table 19. Bulk-density means by treatment-depth combination, post-harvest 1982
Bearbrook clay

	Bulk density			
	Depth (cm)			
Treatment	5	10	15	20
	Mg/m^3			
A	1.06a	1.11abc	1.18	1.43
B	0.97b	1.18ab	1.20	1.35
C	1.02ab	1.07abc	1.15	1.30
D	1.06a	1.14abc	1.21	1.37
E	1.08a	1.06bc	1.05	1.35
F	1.07a	1.19a	1.18	1.33
G	1.00b	1.01c	1.07	1.31
H	1.08a	1.08abc	1.18	1.31

Means at each depth with the same letter are not significantly different ($p \leq 0.05$) by the Waller-Duncan K-ratio test

Figure 11 Bulk Density at Each Depth, Treatment Means

August 1982, Bearbrook Clay



This is consistent with other reported results (Mortensen and Young, 1960; Benoit et al., 1962) that suggested that annual or biannual additions of organic material are necessary if effects are to persist for any length of time. The beneficial effects of sweet clover were not as persistent as those of red clover, as only treatment G still had a low bulk density by post-harvest, 1982.

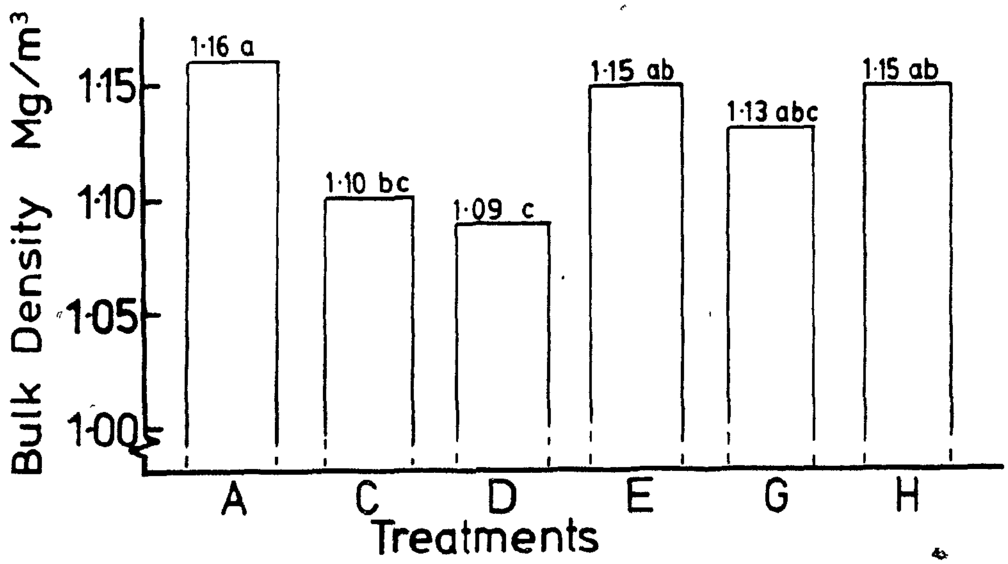
Effect of green manures on soil compactibility

An analysis of variance of the six treatments that were in corn in 1982 shows that the mean bulk density of all rows (compacted and non-compacted, Table 9) was affected by the cropping system at the 0.05 level of significance at a depth of 0-5 cm. Treatment D, which had a well-established stand of vetch in 1982, had a significantly lower mean bulk density than treatments A, E, and H (Fig. 12). An analysis of variance was also performed on the difference between the bulk densities of non-compacted and compacted rows of each treatment. Although data in Fig. 13 show that the smallest difference was visibly in treatment D, the analysis of variance showed the probability of a higher F statistic to be just 0.0549. The small sample size and high variability within treatments likely caused this result. Although the coefficient of variability was reduced from 41% to 26% with a square-root transformation, the probability of a greater F statistic did not decrease.

The vetch in the intercrop plot may have decreased compaction during harvesting by spreading the pressure more evenly over the soil surface or perhaps by keeping the surface soil at an optimal moisture content to withstand compactive forces. Felt (1965) discussed this phenomenon in clay soils of substantial aggregation, as was the case with this soil. According to him, the aggregates in these soils often swell at a certain moisture level to give the

Figure 12 Bulk Density at 0-5cm, Treatment Means

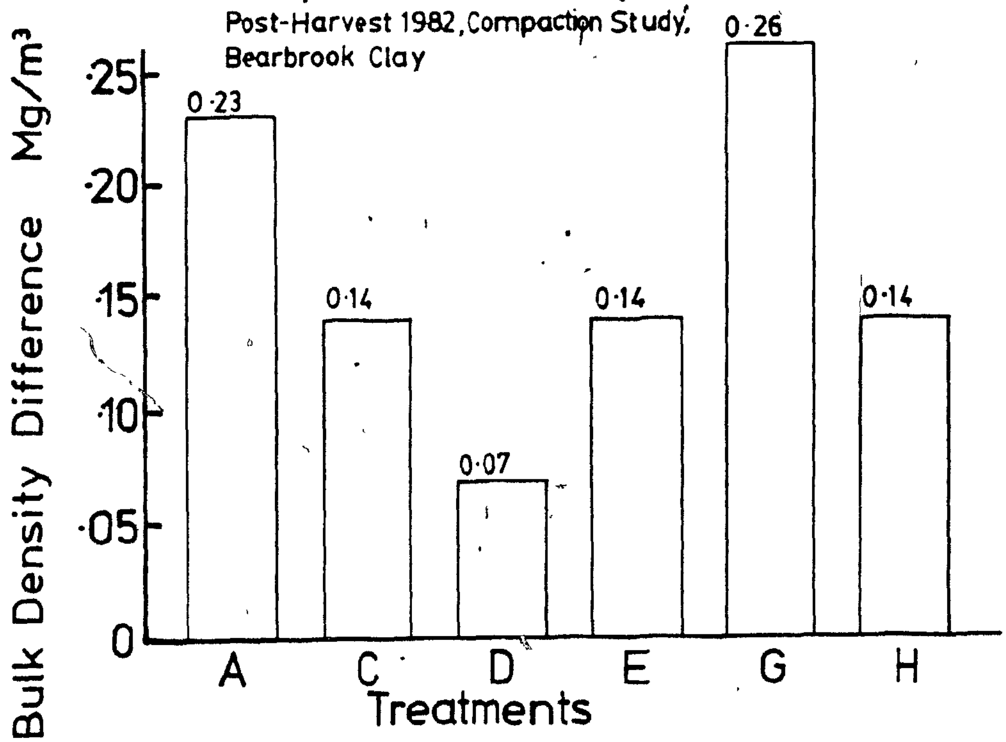
Post-Harvest 1982, Compaction Study, Bearbrook Clay



Means with the same letter are not significantly different ($p \leq 0{\cdot}05$) by the Waller-Duncan K-ratio test

Figure 13 Difference between Bulk Densities of Compacted & Uncompacted Plots at 0-5 cm

Post-Harvest 1982, Compaction Study, Bearbrook Clay



soil greater resistance to compaction than it would have at a lower moisture content. Moisture content was measured at the same time as bulk density in this study and there was a significant treatment effect at 0-5 cm ($p \leq 0.01$). Gravimetric moisture values in treatment D were significantly higher than those of several other corn treatments (Table 21). Felt's explanation is, thus, quite plausible from the results obtained.

Moisture retention

There were no significant treatment effects on gravimetric water contents at any point of measurement during moisture desorption from -0.06 to -15 bars in any sampling period. Volumetric moisture contents were calculated for 1982 data. It was anticipated that the treatment effects on bulk density in 1982 might mask effects that would be apparent by measuring volumetric water contents (Jamison, 1953; Stevenson, 1974). This was not the case. Several authors have indicated that organic-matter additions rarely affect retention properties in clay soils (Jamison, 1953; Jamison and Kroth, 1958; Reeve et al., 1973).

There was a decline in gravimetric moisture content at field capacity and in available-water capacity during the three years (Table 20) in response to mechanical disturbance. With the decrease in the number of large aggregates came an increase in the macropore volume at the expense of micropore space, a volume which for the most part is drained by gravitational forces and is not considered plant available. This decline does not seem to have been sufficient to make moisture a limiting factor in this soil.

Although, with regard to moisture retention, there was no inherent structural improvement due to the addition of organic matter, green

Table 20. Gravimetric moisture-content means for selected pressures during moisture desorption and available-water capacity, 1980-2 Bearbrook clay

	Gravimetric moisture content			
Sampling period	-0.10 bar	-1.0 bar	-15.0 bar	AWC
	%			
Untreated	44.2±2.3			
bh 80	39.0±3.0	37.1±3.0	29.8±1.5	9.2±2.5
Aug. 81	36.8±2.1			
bpl 82	38.1±2.2		29.3±1.4	8.8±1.8
ph 82	35.5±2.0	33.6±1.8	28.8±1.2	6.7±1.5

Legend

bpl - pre-planting　　bh - pre-harvest　　ph - post-harvest

Table 21. Gravimetric moisture contents, by treatment at each depth, post-harvest (October 29),1982
Bearbrook clay

	Gravimetric moisture content			
	Depth (cm)			
Treatment	5	10	15	20
	%			
A	25.8bc	31.9ab	35.6	33.7
B	32.0a	34.7a	33.6	33.9
C	23.8c	30.8bcd	33.6	35.0
D	29.9ab	33.2ab	33.0	33.5
E	24.6c	28.2d	31.2	32.6
F	31.4a	32.1ab	32.8	33.5
G	26.5bc	31.7abc	35.2	35.1
H	25.6bc	28.7cd	32.0	32.6

Means at each depth with the same letter are not significantly different ($p \leq 0.05$) by the Waller-Duncan K-ratio test

manuring did have some benefit regarding soil moisture levels. As the fall of 1982 was extremely dry, it was thought to be an optimal time to examine field moisture contents. An analysis of variance was performed on gravimetric field moisture content at 5-cm-depth intervals to 20 cm. There were significant effects due to treatment at 0-5 cm ($p \leq 0.01$) and at 5-10 cm ($p \leq 0.01$). The means test ($p \leq 0.05$) at 0-5 cm indicated that treatments B and F, cropped to clover and barley in 1982, had significantly higher moisture contents than all other treatments except treatment D, the corn/legume intercrop treatment (Table 21). These three treatments were the only ones with mean values above the permanent wilting point (Table 20). The same trend was apparent from 5-10 cm though the differences between treatments were not as great. As there was almost complete plant coverage of the soil surface in these three treatments, moisture loss was reduced. The effect was evident to a depth of 10 cm.

Water flow

No significant effects of treatment on saturated hydraulic conductivity or infiltration occurred in any sampling period. Results within treatment-replicate combinations were highly variable for both the falling-head method and the modified infiltration procedure. This necessitated the use of the non-parametric test, Friedman's 2-way analysis of variance, a test essentially as powerful as the parametric analysis of variance (Siegel, 1956). No significant χ_r^2 statistics resulted from this test.

Treatment means from the falling-head analysis at pre-harvest, 1980 ranged from 0.007 to 0.371 m/day. Prior to cultivation 1982, using the modified infiltration procedure, the time required for the initial 2 cm of water to infiltrate varied from 7 to 303 seconds. At post-harvest, 1982, the second 2-cm infiltration was thought to be a better measure of infiltration in the plow layer as the soil was so dry during the test. Treatment means ranged from 22 to 792 seconds.

Many authors have indicated that additions of organic matter will improve infiltration, particularly if there has been an improvement in aggregate distribution (Browning and Milam, 1944; Joffe, 1955; Benoit et al., 1962; Allison, 1973). There were no significant treatment effects on soil organic-carbon levels in this study. Only at post-harvest, 1982 were water flow and wet-aggregate distribution determined at approximately the same time. In neither case were there any significant differences among treatments. The absence of effects on soil organic carbon and wet-aggregate distribution explains the absence of treatment effects on infiltration. Although there were effects in dry-aggregate distribution, this did not aid infiltration, partly because the small aggregates created were not stable in water and partly because of the moisture conditions particular to the soil at the sampling times. As the soil was very dry during the 1982 sampling periods, the rapid addition of water caused immediate swelling of the surface aggregates and reduced the large pore spaces in the testing zone. This rapid swelling likely would have reversed any beneficial structural effects that would be associated with an improved dry-aggregate distribution. The swelling pressures were sufficiently great to force the cylinder of an air-entry permeameter (Topp and Binns, 1976) out of the soil.

Table 22. Correlation coefficients (r) of measured parameters Bearbrook clay

	Parameter											
	DryAI 1	WetAI 2	PC 3	ρb 4	FCW06 5	FCV06 6	AWW 7	AWV 8	PWPW 9	PWPV 10	I 11	OC 12
1		.66**	-.38T	-.39T	ns	-.57**	ns	ns	ns	-.42*	-.57**	ns
2			.44*	ns	ns	ns	ns	ns	ns	ns	ns	ns
3				ns	ns	ns	ns	ns	ns	ns	.45*	ns
4					ns	.42*	ns	ns	ns	.66**	ns	ns
5						.70**	.84**	.81**	.73**	ns	.51*	ns
6							.57**	.74**	.53**	.75**	.52**	ns
7								.96**	ns	ns	ns	ns
8									ns	ns	ns	ns
9										.53**	.59**	ns
10											.37T	ns
11												ns

ns Not significant at the 0.10 level of probability

T Significant at the 0.10 level of probability

* Significant at the 0.05 level of probability

** Significant at the 0.01 level of probability

Correlations between measured parameters

A matrix of correlation coefficients is presented in Table 22. Parameters examined were: dry-aggregate distribution (dryAI); wet-aggregate distribution (wetAI); stability (PC); bulk density (ρb); gravimetric and volumetric water content at field capacity at -0.06 bars (FCW06 and FCV06), permanent wilting point (PWPW and PWPV), and available-water capacity (AWW and AWV); time required for infiltration of a second 2-cm addition of water (I); and soil organic carbon (OC).

Of greatest interest is that soil organic-carbon levels were not significantly correlated with any measured physical parameter. Based on the literature, no significant correlations with moisture-retention properties were expected. It was anticipated, however, that some significant correlations with aggregate indices and bulk density would exist and possibly one between time for infiltration and organic carbon because of the significant correlation ($p \leq 0.01$) between this parameter and dry-aggregate distribution. It is very unlikely that organic matter did not have any influence on these parameters. Different organic components will affect different physical parameters (Harris et al., 1966; Allison, 1973; Lowe, 1978) but rarely does some component not affect some physical parameter (Allison, 1973). The Walkley-Black method determines readily-oxidizable carbon and is not designed to measure subtle shifts in, say, polysaccharide content, which Lowe (1978) estimated comprises only 5-20% of total soil organic matter. Greenland's (1965) conclusion, mentionned previously, seems to account adequately for the failure to have any significant correlations with organic carbon.

The significant correlation between time for infiltration and dry-aggregate distribution was a negative one. With an improvement in dry-aggregate distribution came a decrease in the amount of time for a certain amount of water to infiltrate. That the significant treatment differences in dry-aggregate distribution did not produce significant treatment effects in the time required for infiltration, supports the hypothesis that aggregate swelling during testing masked any effect. The significant correlation ($p \leq 0.05$) of infiltration and stability was most likely an artifact of the relationship between dry-aggregate distribution and stability (significant at $p \leq 0.10$). The significant relationships of infiltration with gravimetric and volumetric field capacity can be tied to their relationship with dry aggregation, in that the increased macropore space associated with an improved dry-aggregate distribution resulted in a lower field-capacity value and more rapid infiltration. The relationships with gravimetric and volumetric permanent wilting point (PWP) were likely an artifact of the relationship of PWP with field capacity. PWP is not affected by soil structural factors as its value is largely a function of the surface area of the soil particles.

The relationship between bulk density and dry-aggregate distribution was significant at the $p \leq 0.10$ level only and bulk density was not correlated significantly to any other aggregate index. It is not known why the correlation was not stronger in light of the similarities in treatment effects in the two parameters. As bulk density was not significantly correlated to any gravimetric moisture measurements, the relationship with volumetric field capacity and PWP is most likely a function of the mathematical manipulation used to determine volumetric moisture values ($\vartheta = w \rho b$). The same is likely true, through the relationship between bulk density and dry-aggregate distribution, for the significant relationships between dry-aggregate distribution and volumetric field capacity and PWP. There were no significant correlations of wet-aggregate distribution with parameters other than aggregation indices even though wet-aggregate distribution was significantly correlated ($p \leq 0.01$) to dry-aggregate distribution. Of particular note is that there was no significant correlation of wet-aggregate distribution with infiltration time.

Crop yield

An analysis of variance was performed on the total economic crop yield produced by each rotation: i.e. silage corn and barley grain (Table 23). The results showed that there was a significant effect due to year ($p \leq 0.05$) and a treatment x year interaction ($p \leq 0.01$). There was no effect of treatment on total rotation yield. The interaction was caused by the difference in yield produced by barley and corn, as each year two different treatments were cropped to barley and clover. The year means indicate that 1981 was the most favourable year for corn growth and 1982 the worst.

Two regressions analyses were performed using total rotation yield (Y1) and mean annual corn yield (Y2) as dependent variables and 12 independent variables: dry-aggregate distribution (dryAI); wet-aggregate distribution (wetAI); stability (PC); bulk density (ρb); gravimetric and volumetric field capacity (FCW and FCV), permanent wilting point (PWPW and PWPV), and available-water capacity (AWCW and AWCV); time required for infiltration of a second 2-cm addition of water (I); and soil organic carbon (OC). The purpose of the regression was to determine if measured physical parameters could explain the variation in yields.

The results demonstrated the difficulties of yield analysis in short-term rotation experiments. The best equation for Y1 was:

$$Y1 = -17.3 + 62.6\rho b - 1.10PWPV.$$

Table 23. Crop yields, 1980-2
Bearbrook clay

	Crop yield				
	Year			Total	Mean annual corn yield
Treatment[1]	1980	1981	1982		
	t/ha				
A	7.98	5.88	5.91	19.8	6.59
B	8.92	6.18	2.92	18.0	7.55
C	2.91	6.86	5.68	15.4	6.27
D[2]	5.08	11.7	2.74	19.5	6.51
E	3.89	9.34	6.71	19.9	8.02
F	8.26	12.3	2.74	23.3	10.3
G	8.22	2.32	8.66	19.2	8.44
H	7.19	1.86	6.88	15.9	7.04
Mean	6.56	7.06	5.01		

1 Data from plots receiving 150 kg/ha nitrogen

2 Corn yield only

The model was significant at the 0.01 level of probability. The β_1 value was significant at the 0.01 level of significance, β_2 at the 0.05 level. This equation explained 44% of the variation in total rotation yield. The equation suggests that a higher bulk density will produce a higher yield. In this experiment, this was the case because the treatments with the lowest bulk density (treatment G in particular) did not have corn in one year of three and, thus, total rotation yield was lower, though not significantly. Also the high correlation between bulk density and volumetric permanent wilting point (r=.66) shows that the factors were probably not independent. The best equation expressing the relationship between mean annual corn yield and measured parameters was:

$$Y2 = 22.8 - 0.404FCW.$$

The model was significant at the 0.05 level of probability. The β_1 value was significantly different from zero ($p \leq 0.05$). This equation only explained 24% of the variation in mean annual corn yield.

Although there were no significant differences between total rotation yields, indicating that green manuring was contributing something to crop performance, this could not be explained by regression analysis. With less than 50% of the variation in yield explained by the models, it is likely that climatic variability, a major problem in short-term rotation studies, and soil fertility factors, particularly available nitrogen, were paramount in determining yields.

FRANKLIN GRAVELLY LOAMY SAND

Background data

All three cropping seasons were climatically abnormal for this site. The 1980 and 1981 seasons were wetter than average, such that moisture was not a limiting factor to plant growth as is usually the case. The 1982 growing season was extremely dry (Table 24).

Biomass and % N for incorporated material is presented in Table 25. As with the intercrop treatment on the Bearbrook soil, difficulties in determining the right management programme for intercropping resulted in negligible production of the undersown legume in 1980 and 1981. The 1980 'Plowdown' stands were estimated visually to cover only 35% of the area of the experimental units. Although buckwheat biomass in treatment D was not determined, from visual observation, a strong stand existed and the biomass produced was not likely different from that produced in 1981 and 1982. Buckwheat stands contained very few weeds while vetch was not as competitive. The low tissue-N levels in vetch plots are a result of low tissue-N levels in weeds which were included in all tissue-N estimates.

Soil organic carbon

Treatments did not significantly affect soil organic-carbon levels in any sampling period. Levels remained fairly constant, though there was a slight decline after the first year of cropping (Fig. 14). The type or amount of residue incorporated was obviously not a factor in determining soil organic-carbon levels. Unfortunately, no analysis of the organic material was performed, but from visual inspection it appeared that there was an increase

Table 24. Total rainfall
Franklin gravelly loamy sand

	Year		
Month	1980	1981	1982
	cm		
May	nd	5.0	2.0
June	3.4 (5)*	16.6	7.8
July	8.4	7.6	9.4
August	18.3	22.3	9.8
September	12.0	14.7 (24)	9.8
October	4.9	nd	2.5 (14)
Total	47.0	66.2	41.3

* Number in brackets is the day of the month recording began or ended

nd Not determined

Table 25. Characterization of green manures used on Franklin gravelly loamy sand

	Treatment						
Measurement	B	C	D	E	F	G	H
1980 Dry matter (t/ha)			nd	neg			0.88[1]
% N			nd	nd			nd
1981 Dry matter (t/ha)	4.47			neg		6.27	
% N	1.06			nd		1.28	
1982 Dry matter (t/ha)		4.49		2.00[2]	5.56		
% N		1.97		nd	1.78		

nd Not determined

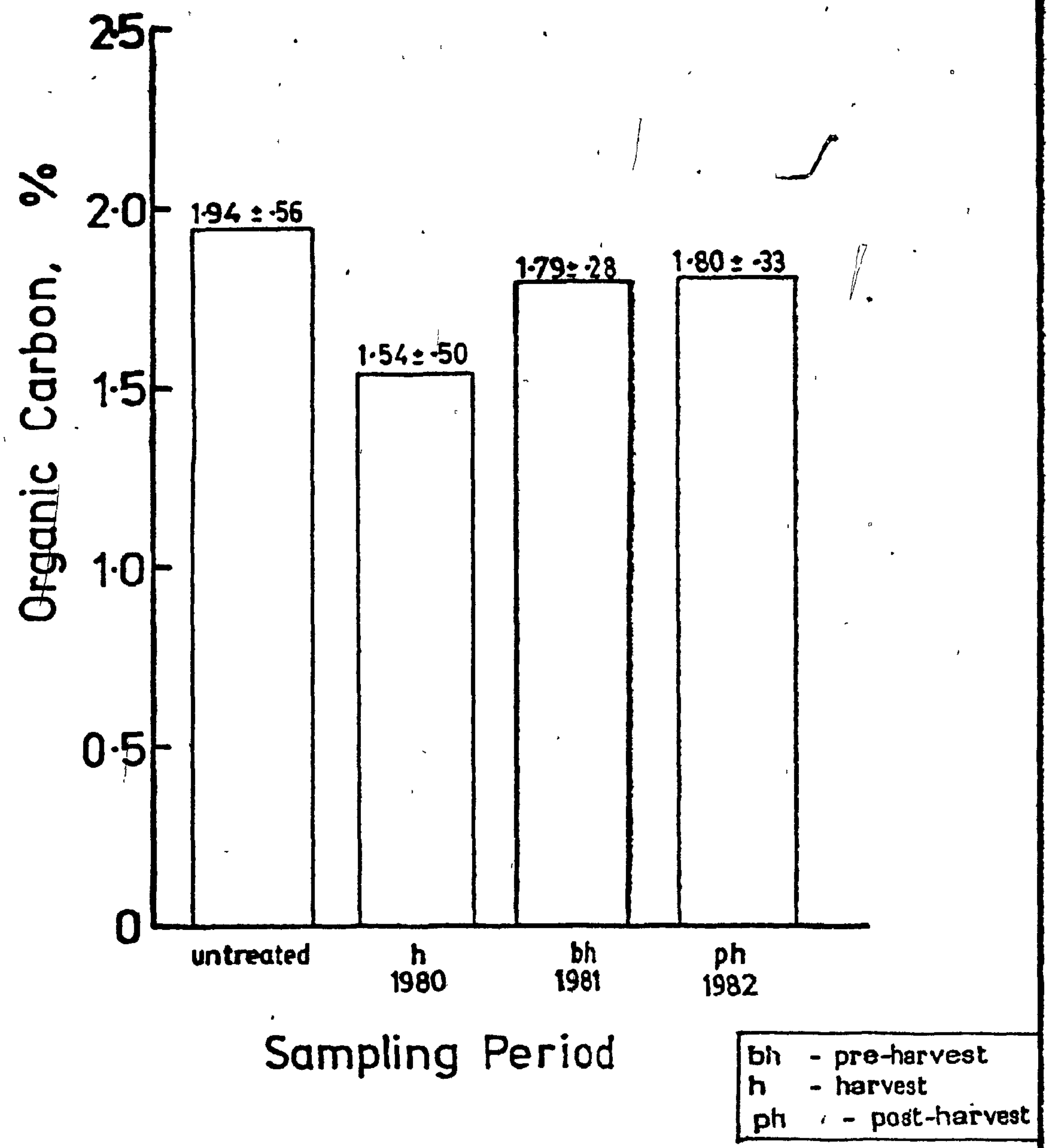
neg Negligible biomass produced

[1] Estimated by multiplying average biomass produced in three meter squared sections of the experimental units by the percent of the experimental unit covered by 'Plowdown', estimated visually at 35%.

[2] Does not include corn stubble

Figure 14 Soil Organic Carbon, Sampling Period Means

1980-1982, Franklin Gravelly Loamy Sand



in the coarse organic-matter fraction. This may have occurred at the expense of other organic-matter components because the sampling-period means remained fairly constant. Organic carbon effects in the sub-plots and the laboratory experiment will be discussed with the effect of N fertilizer rates on aggregation, and the laboratory experiment, respectively.

Aggregation (field experiment)

There were no significant effects due to treatment in any sampling period. Cultivation had a great impact, however, on the amount of soil that was aggregated. From Fig. 15, it is apparent that site preparation reduced the amount of aggregated non-sand soil and that in 1980 and 1981, compaction was a strong aggregating force. That this did not occur in 1982 likely means that the ability of this soil to withstand the forces of cultivation and compaction declined. The extent to which this decline was a function of the dry season could not be determined. Besides organic-carbon levels, the effect of pH and calcium on aggregation was examined as these two factors can be a limitation to aggregate formation and stabilization. There were no significant effects due to treatment on calcium but there was a significant effect on pH ($p \leq 0.05$) at harvest, 1980. The means test (Table 26) shows that all plots planted in corn were not significantly different from each other. Treatments D and H, whose plots were cropped to green manures in 1980, had the highest pH levels, substantially higher than the background level of 5.3 ± 0.2. Treatment D was significantly higher than treatments A (monoculture corn), B (buckwheat in 1981), and F (vetch in 1982), while H was significantly different from treatments A and F. This effect on pH, however, did not affect aggregation. Differences in pH were neutralized by the addition of lime in the spring of

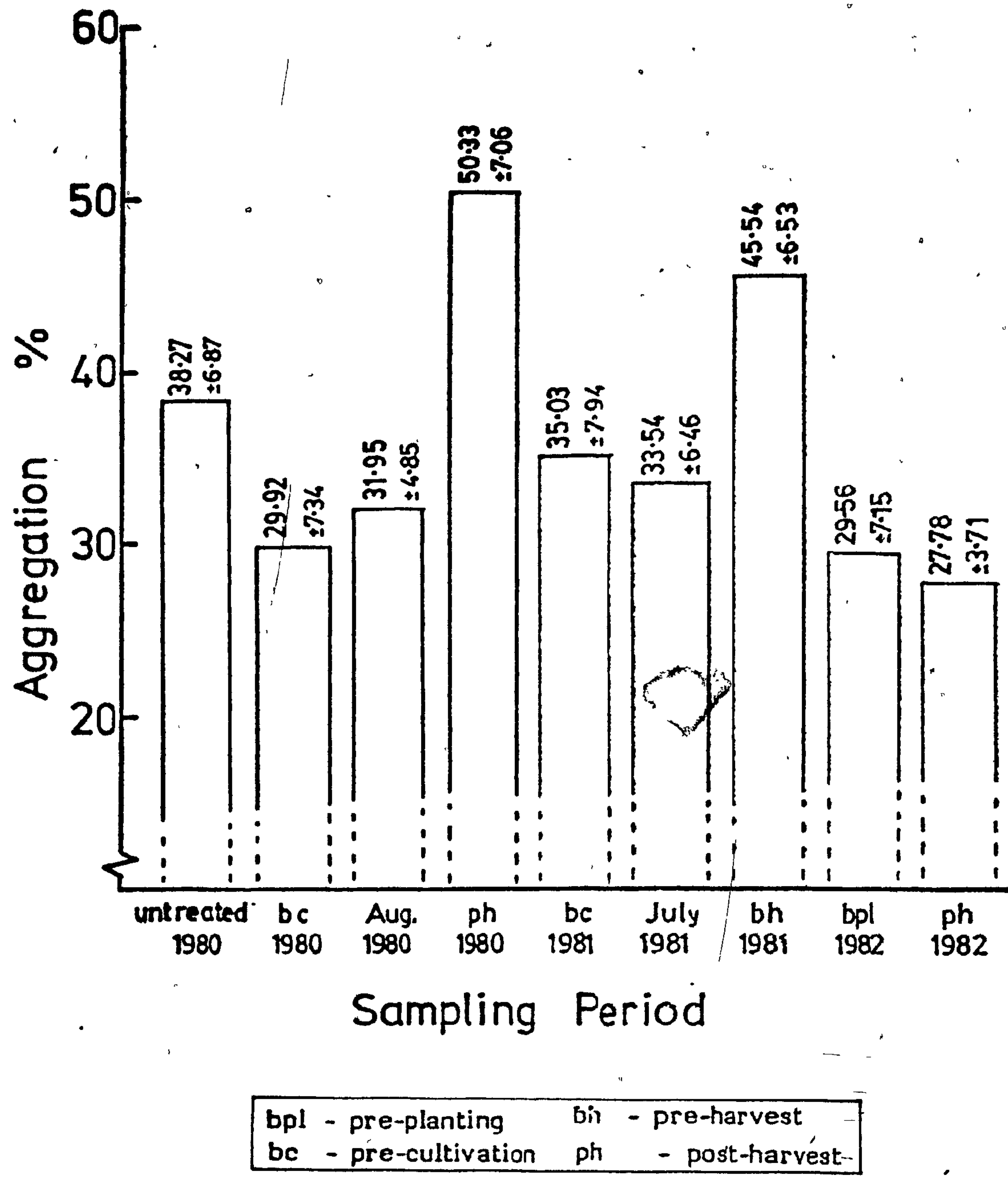
Table 26. pH means at harvest 1980
Franklin gravelly loamy sand

Treatment							
A	B	C	D	E	F	G	H
5.1c	5.2bc	5.3abc	5.8a	5.4abc	5.1c	5.5abc	5.7ab

Means with the same letter are not significantly different ($p \leq 0.05$) by the Waller-Duncan K-ratio test

Figure 15 Aggregation Sampling Period Means

1980–1982, Franklin Gravelly Loamy Sand



1981. There was also a significant interaction of treatment with depth, post-harvest, 1982 ($p \leq 0.01$). Treatments having buckwheat in the rotation in 1980 or 1981 had a more uniform pH throughout the plow layer (Fig. 16). Again, no significant treatment effects on aggregation resulted.

Aggregation (laboratory experiment)

Although no significant treatment differences resulted from the field study, treatments with buckwheat in the rotation were often found to have the highest aggregation index. The laboratory study showed that under controlled conditions, incorporating buckwheat resulted in a significantly higher level of aggregation ($p \leq 0.05$) than incorporating vetch (Table 27).

This result can be explained by examining soil levels of organic carbon, pH, and calcium. Soil calcium levels were significantly affected by treatment ($p \leq 0.05$). With vetch incorporated, more calcium was available than with buckwheat incorporated (Table 27), suggesting that calcium was involved in aggregate stabilization in the buckwheat-incorporated soil to a greater extent than in the vetch-incorporated soil. This resulted in more aggregation. Soil with vetch incorporated had a higher organic-carbon level than soil with buckwheat incorporated though this was only significant at the $p \leq 0.10$ level of significance (Table 27). This result suggests, though, that decomposition occurred at different rates, perhaps yielding different organic compounds that affected aggregation in different ways. The vetch, under these controlled conditions, appears to have decomposed more rapidly, as would be expected from the literature (Allison, 1973; Warman, 1980). It is likely that the buckwheat, with a slower rate of decomposition, had a more favourable effect on aggregation because readily decomposable material often causes aggregate

Figure 16 . Changes in Soil pH with Depth

Post-Harvest 1982, Franklin Gravelly Loamy Sand

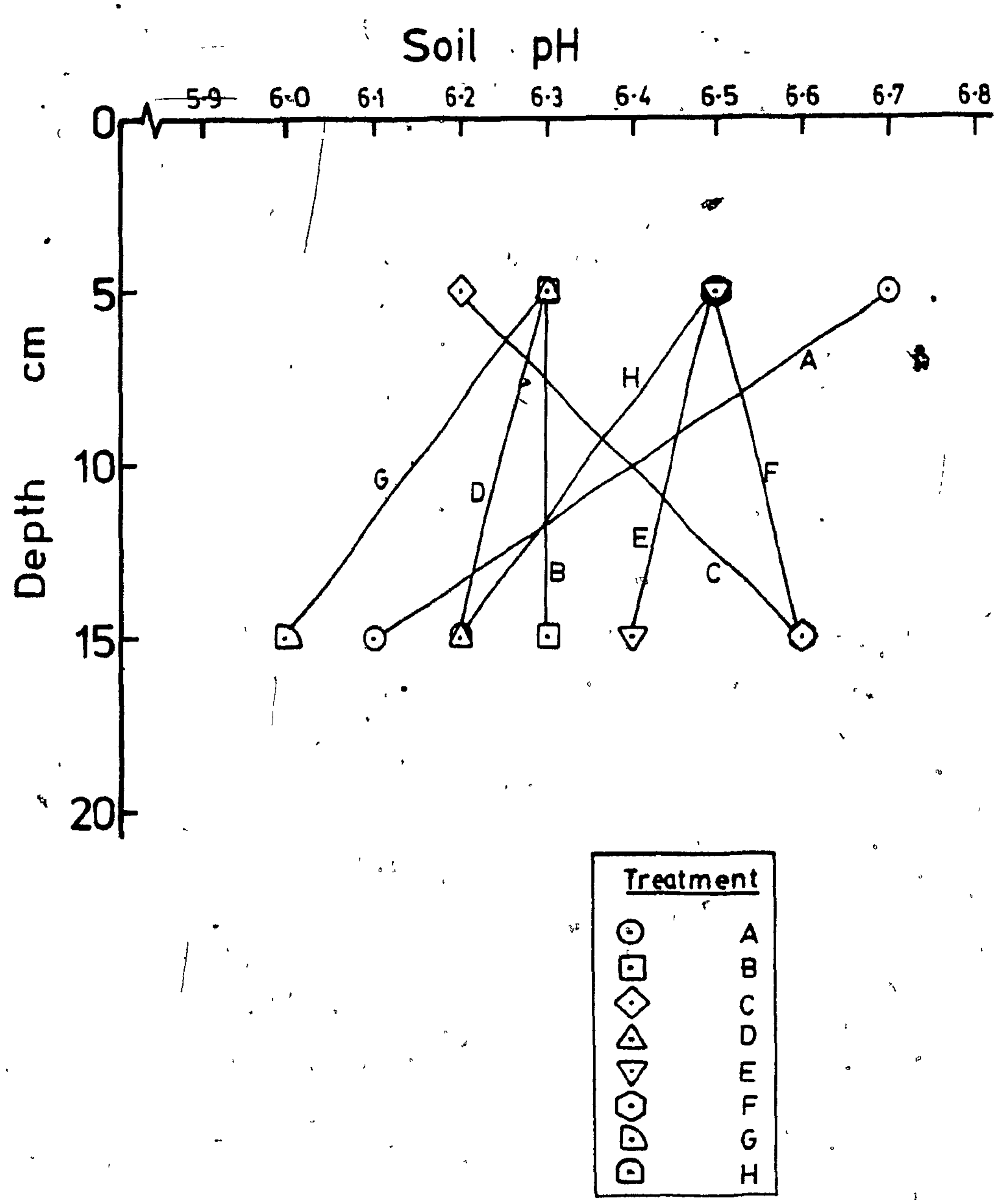


Table 27. Effect of incorporated plant material on soil aggregation, soil calcium and soil organic carbon
Laboratory experiment
Franklin gravelly loamy sand

Plant material	Aggregation (%)	Calcium (ppm)	Organic carbon (%)
Buckwheat	35.68a	965b	1.68
Vetch	29.58b	1060a	1.80

Means with the same letter are not significantly different ($p \leq 0.05$) by Duncan's new multiple range test

Table 28. Effect of aggregating force on soil aggregation
Laboratory experiment
Franklin gravelly loamy sand

Aggregating force*					
1	2	3	4	5	6
33.62ab	29.18b	34.91a	33.20ab	30.40ab	34.40a

Means with the same letters are not significantly different ($p \leq 0.05$) by the Waller-Duncan K-ratio test

* See page 36 for the descriptions of the aggregating forces

stabilization to occur rapidly, but the effects do not persist as long as the effects produced by more slowly decomposable material (Rennie et al., 1954). This relates particularly to polysaccharides produced by the decomposing material which were not measured in this study.

Soil pH levels were affected significantly by plant material incorporated (Pl) ($p \leq 0.01$), the method of incorporation (Pr) ($p \leq 0.05$), and there were significant interactions of plant material incorporated with method of incorporation ($p \leq 0.01$), plant material incorporated with aggregating force applied (trt) ($p \leq 0.05$), and method of incorporation with aggregating force applied ($p \leq 0.05$). For the most part, soil with vetch incorporated had higher pH levels though the significant differences between means of factors measured were almost always less than 0.3 pH units and, from a practical viewpoint, negligible.

Cycles of wetting and drying produced the most aggregation, only significantly different, however, from cycles of freezing and thawing ($p \leq 0.05$). The optimal moisture content, as described by Hartmann and De Boodt (1974), was also significantly different from cycles of freezing and thawing (Table 28). Soil organic-carbon levels, soil pH, and soil calcium were not significantly affected by aggregating forces. The pH analysis of interactions of plant material with aggregating force and method of incorporation and aggregating force (Fig. 17 and 18), suggests that the effect was related to soil pH, though again, the significant differences were very small in practical terms.

Effect of N fertilizer rates on aggregation

Nitrogen fertilizer rates had no significant effect on aggregation in any sampling period. This is explained by the absence of effects on soil organic

Figure 17 Effect on pH of the Response of Aggregating Force to Incorporated Plant Material.

Laboratory Experiment, Franklin Gravelly Loamy Sand

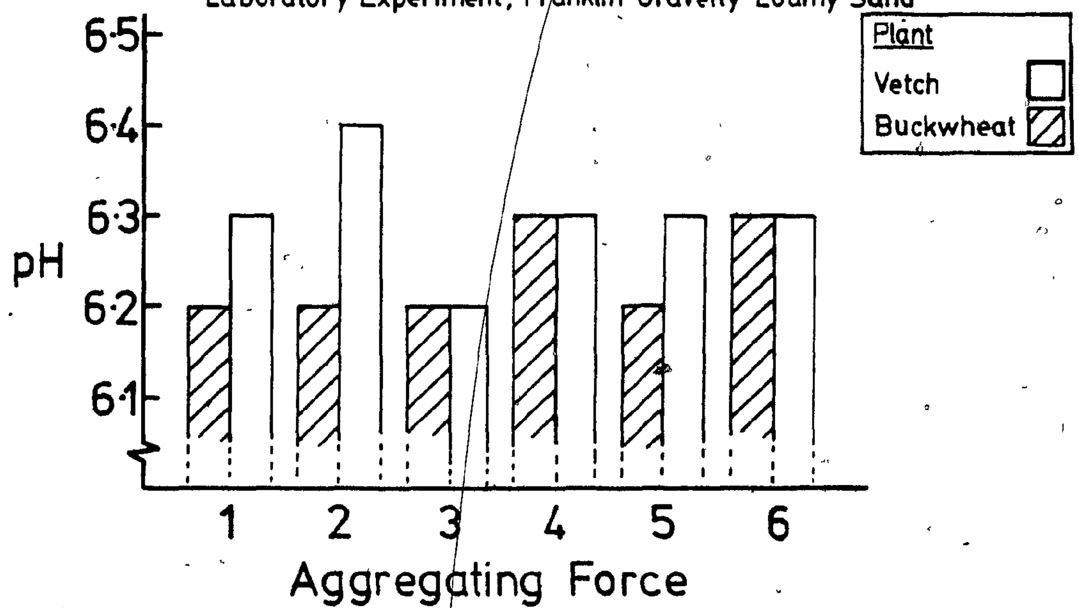
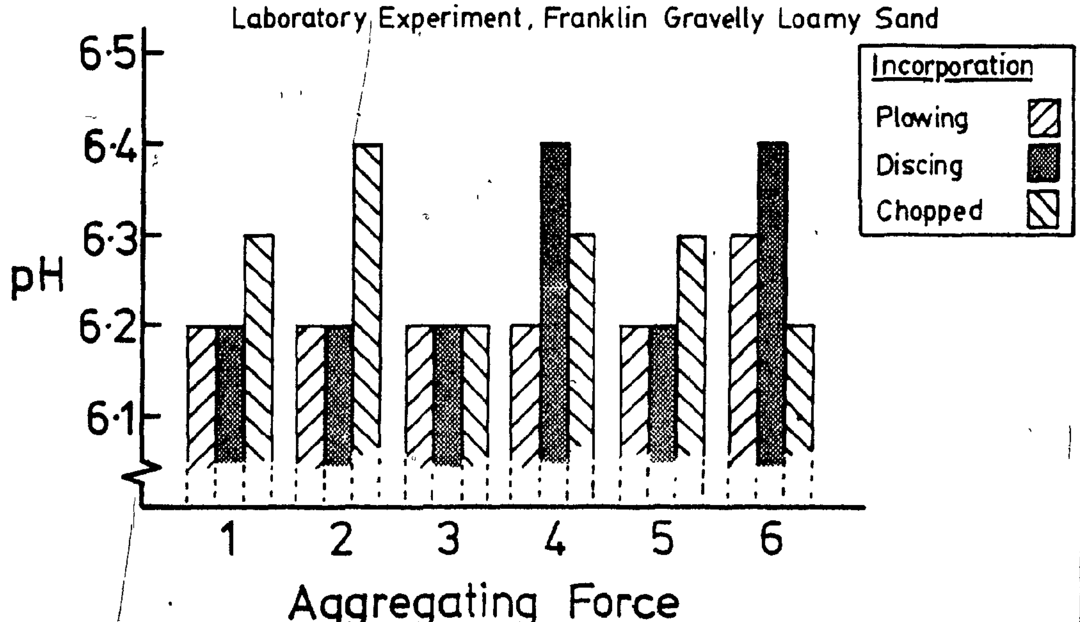


Figure 18 Effect on pH of the Response of Aggregating Force to Method of Incorporation.

Laboratory Experiment, Franklin Gravelly Loamy Sand



carbon, soil pH, soil calcium or corn yields.

Bulk density

There were no significant effects of treatment on bulk density in any sampling period. The sampling-period-bulk-density means declined slightly in 1982, after increases in 1981, though, by standard deviations, this decline was not significant (Fig. 19). The absence of treatment effects could be a function of the vagaries of sampling a stony soil. As the soil contains 26% coarse fragments by volume, variability in coarse-fragment content within the sampling volume of the radiation-scattering gauge was inevitable and this variability might have been great enough to hide any differences in bulk density due to treatment. Another possibility is that the proportion of coarse fragments by weight was sufficiently large (39%) and inert in terms of interaction with organic matter, that any effects that did occur were too diluted by the coarse-fragment fraction to be apparent. The absence of effects in aggregation and soil organic-carbon levels due to treatment, however, supports the conclusion that there was no intrinsic effect of rotation on bulk density and, therefore, no improvement in bulk density.

An examination of the bulk density at 0-5-cm depth at post-harvest 1981 and 1982 suggests, though the differences were not significant at the 0.05 level, that treatments in buckwheat and vetch had lower bulk-density values because the soil was not compacted with harvesting machinery (Table 29). Overall, this was not a good result because, in the first two years, aggregation seemed to improve with compaction. Data in table 29 suggest, however, that there was no relationship between the bulk-density values at 0-5 cm and their associated aggregation index at 0-10 cm.

Figure 19 Bulk Density, Sampling Period Means

1980-1982, Franklin Gravelly Loamy Sand

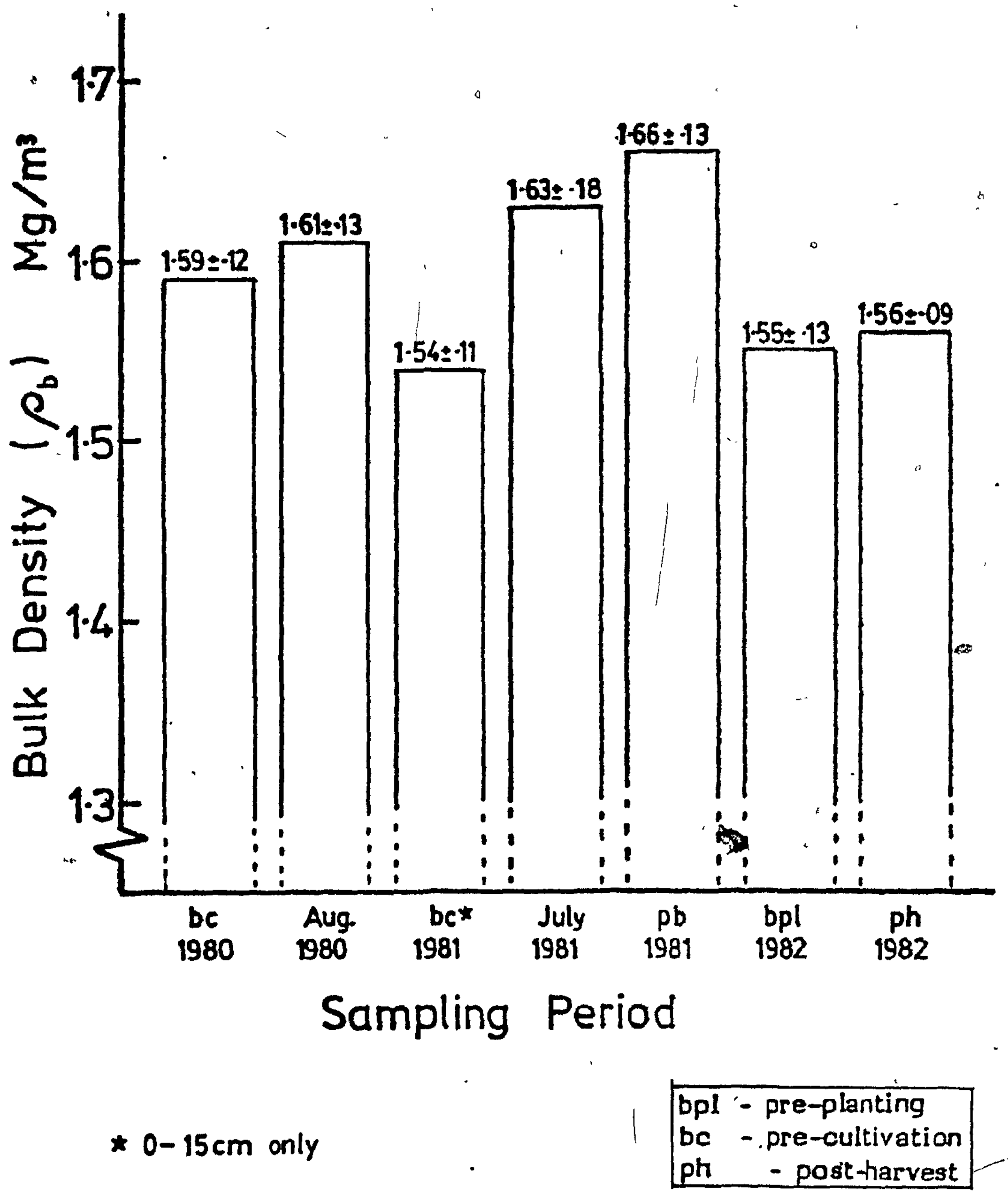


Table 29. Bulk density and aggregation means from post-harvest sampling periods
Franklin gravelly loamy sand

	Post-harvest 1981		Post-harvest 1982	
	Bulk density (0-5 cm)	Aggregation (0-10 cm)	Bulk density (0-5 cm)	Aggregation (0-10 cm)
Treatment	Mg/m^3	%	Mg/m^3	%
A	1.70	34.16	1.49	23.27
B	<u>1.61</u>	51.97	1.48	22.33
C	1.68	41.32	<u>1.40</u>	18.96
D	1.74	43.37	1.55	30.45
E	1.65	36.54	1.51	23.37
F	1.81	39.08	<u>1.31</u>	21.37
G	<u>1.56</u>	39.04	1.48	24.98
H	1.67	39.65	1.56	24.37

Underlined values are the lowest in each sampling period

Saturated hydraulic conductivity (Ksat)

There were no significant effects due to treatment in any sampling period. Table 30 shows that Ksat means varied inversely with bulk density means. With decreases in bulk density in the field, it is likely that Ksat increased, though the magnitude of the increase was likely less than demonstrated by Table 30. Ksat values in the field would be lower than those recorded in laboratory tests due to the presence of coarse fragments (Dunn and Mehuys, 1983). It had been hypothesized that the green manures would decrease Ksat due to the addition of coarse organic material which would reduce the rate of flow (Barley, 1953; 1954). Although from visual inspection there appeared to have been an overall increase in coarse organic material, bulk density changes were more important in determining Ksat.

Moisture retention

There were no significant treatment effects on moisture retention in any sampling period. The amount of green manures incorporated was not sufficient to bring about significant differences between treatments, although all treatments with buckwheat in the rotation (treatments B, C, and D) had the highest moisture contents (not significantly different at the 0.05 level from any other treatments) at all points of measurement during moisture desorption in the post-harvest, 1982 sampling period. Only treatment F had higher available-water capacity values. This is an interesting trend which suggests that, in the long term, additions of buckwheat will increase the moisture holding capacity of the soil.

Table 30. Saturated-hydraulic-conductivity treatment means, 1980-2, measured by the falling-head method on the less than 2-mm fraction Franklin gravelly loamy sand

	Year			
	1980	1981	1982	
Treatment			pre-planting	post-harvest
	Saturated hydraulic conductivity (m/day)			
A	5.59	2.47	4.36	4.20
B	3.11	2.46	3.78	4.15
C	2.30	2.99	4.81	3.11
D	4.37	1.92	3.25	4.66
E	3.44	2.72	5.67	4.18
F	2.59	2.14	3.16	4.49
G	4.72	3.16	5.10	4.77
H	4.08	2.60	4.63	5.13
Mean	3.77	2.54	4.34	4.34
	Bulk density (Mg/m^3)			
Mean	1.31	1.36	1.26	1.27

Table 31. Gravimetric moisture-content means for selected pressures during moisture desorption and available-water capacity, 1980-2 Franklin gravelly loamy sand

Sampling time	Bulk density	Gravimetric moisture content -0.10 bar	-0.33 bar	-15.0 bar	AWC.10
	Mg/m^3	%			
ph 80	1.31	16.7±3.0	14.7±2.6	10.8±2.1	5.9±1.4
Aug. 81	1.36	18.1±1.1	16.0±1.3	11.1±0.6	7.0±0.9
bpl 82	1.26	15.2±1.4	13.5±1.2	9.2±0.8	6.0±0.8
ph 82	1.27	16.4±1.2	14.6±1.2	10.0±1.2	6.4±1.0

Legend

bpl - pre-planting

ph - post-harvest

Moisture-retention means varied directly with mean bulk densities (Table 31). By standard deviations, there were only differences between some means in the 1981 and pre-planting, 1982 sampling periods. The highest moisture contents at each point of measurement were associated with the highest bulk density, that of the 1981 sampling period. Because so much of this soil comprises single sand grains, dense packing of particles was required to keep void spaces from becoming too large and drainable by gravitational forces. The loosening of the soil produced an undesirable effect: losses in moisture holding capacity.

No significant treatment differences occurred in field moisture contents in any sampling period over a wide range of soil moisture conditions. The potential for vetch and buckwheat to reduce moisture losses from the soil surface was not evaluated.

Correlations between measured parameters

Eleven physical parameters were examined for their degree of association: aggregation (KI); bulk density (ρb); field capacity at -0.06 bars (FC.06); field capacity at -0.10 bars (FC.10); field capacity at -0.33 bars (FC.33); permanent wilting point (PWP); available-water capacity measured from -0.06 bars (AW06); available-water capacity measured from -0.10 bars (AW10); available-water capacity measured from -0.33 bars (AW33); saturated hydraulic conductivity (Ksat); and soil organic carbon (O.C.).

There were a large number of significant correlations between measured parameters (Table 32). Soil organic-carbon levels were significantly correlated to all moisture-holding-capacity parameters and to saturated hydraulic conductivity at the 0.05 or 0.01 levels of significance. The positive

Table 32. Correlation coefficients (r) of measured parameters Franklin gravelly loamy sand

	Parameter										
	KI	ρb	FC.06	FC.10	FC.33	PWP	AW06	AW10	AW33	Ksat	O.C.
KI		.43*	.47*	.47*	.50*	.69**	ns	ns	ns	ns	ns
ρb			ns	ns	ns	ns	ns	ns	ns	ns	ns
FC.06				.99**	.95**	.87**	.83**	.74**	.56**	-.67**	.60**
FC.10					.98**	.85**	.82**	.78**	.61**	-.67**	.57**
FC.33						.83**	.78**	.76**	.68**	-.72**	.64**
PWP							.44*	ns	ns	-.52**	.50*
AW06								.96**	.82**	-.63**	.52**
AW10									.91**	-.58**	.43*
AW33										-.60**	.47*
Ksat											-.71**

ns Not significant at the 0.05 level of probability

* Significant at the 0.05 level of probability

** Significant at the 0.01 level of probability correlation with all moisture-holding-capacity parameters indicates that, on a plot-by-plot basis, increases in soil organic-carbon levels were associated with an increased water holding capacity. Jamison (1953) and Stevenson (1974) have indicated that this is feasible on this kind of soil. On a plot-by-plot basis, increases in organic-carbon levels were associated with a decrease in Ksat, a desirable effect on this soil. The key component of organic matter in producing this correlation was likely coarse organic material (Barley, 1953; 1954). In light of these correlations, high variability within treatment-replicate combinations is likely the reason that there were no significant treatment effects on soil organic-carbon levels, moisture-holding-capacity parameters, or Ksat. Organic carbon was not significantly correlated with aggregation or bulk density. This supports the previous conclusion that there was no intrinsic improvement in bulk density related to organic-matter additions.

That aggregation values were significantly correlated with bulk density ($p \leq 0.05$) may be an indirect result of the response of each of these parameters to mechanical forces applied to the soil. The values of both parameters responded similarly to compaction and cultivation. The significant correlations of aggregation with moisture-holding-capacity parameters are similarly likely also due to parallel responses to these forces. Bulk density was not significantly correlated to Ksat, even though the mean values of each varied in close association with the other (Table 30). The absence of correlation might be a function of the high variability of coarse fragments per unit volume of soil. Ksat was significantly negatively correlated to all moisture-holding-capacity parameters ($p \leq 0.01$). This is likely an artifact of the relationship between organic carbon and moisture-holding-capacity parameters, and organic carbon and Ksat. There was no significant relationship between bulk density and moisture-holding-capacity parameters even though there was an association between sampling-period means. Again, the high variability of coarse fragments might explain the absence of correlation on a plot-by-plot basis.

Corn yields

An analysis of variance was performed on total rotation yield (Table 33). Treatment, year, and the interaction of year with treatment all affected yield at the 0.01 level of significance. The treatment x year interaction was caused by the absence of any yield in two treatments in each year. Year means showed, even more dramatically than at the Rigaud site, the effect of seasonal moisture variability. The 1981 growing season had the highest yield followed by those of 1980 and 1982, the latter being a very poor year for corn. Those treatments that had green manures in the rotation in 1981 fared extremely poorly (treatments G and B). Only treatments C, E, and F had similar yields to those recorded for treatment A because they all had either poor or no corn in 1982.

An attempt was made to determine cause-and-effect relationships between physical parameters (X values) and total rotation yield (Y1) and mean annual corn yield (Y2). The high number of significant correlations between supposedly independent factors made it impossible to properly assess the relationships. As suggested by Sopher and McCracken (1973), an attempt was made to delete many of the highly intercorrelated factors, but this failed to produce any significant models at the 0.05 level of probability.

Table 33. Corn yield, 1980-2
Franklin gravelly loamy sand

	Corn yield				
	Year			Total	Mean annual corn yield
Treatment[1]	1980	1981	1982		
	t/ha				
A	7.78	12.4	1.73	21.9	7.30
B	6.59	0	1.40	7.99	4.00
C	7.19	11.2	0	18.4	9.20
D	0	12.1	2.45	14.6	7.28
E[2]	5.12	11.1	2.51	18.7	6.24
F	7.42	11.2	0	18.6	9.31
G	7.46	0	1.35	8.81	4.40
H	0	11.0	2.83	13.8	6.92
Mean	5.20	8.61	1.53		

1 Yield data averaged over all N fertilizer rates as there were no significant differences ($p \leq 0.05$) between rates

2 Corn and legume harvested

SUMMARY AND CONCLUSIONS

The incorporation of green manures had some beneficial effects on the soil physical properties of the Bearbrook soil. Treatment G (red clover incorporated in 1981) had the highest dry-aggregate-distribution values in the plow layer and the lowest bulk densities from 0-10 cm. Aggregate stability in water was not increased by any treatment. In fact, wet-aggregate distribution and stability results suggested that stability in water decreased slightly. The reason for this is not apparent as no significant changes in soil organic carbon due to treatment occurred in any sampling period.

Infiltration did not increase in response to green manures although this may be because the swelling of very dry aggregates during testing masked differences between treatments. Treatments did not affect the moisture holding capacity of the soil. There was a general decline in the water content of various moisture-holding-capacity parameters with cultivation.

As the application rate of nitrogen fertilizer increased, so did the percentage of small aggregates increase, particularly for treatments whose plots were cropped to red clover. Although this response would be favourable to plant growth for the present soil conditions, the long-term effects of this response would likely be detrimental to crop production.

The practice of intercropping corn with an undersown legume showed the potential to reduce surface compaction in a dry year by reducing evaporation from the soil surface and keeping aggregates sufficiently moist to withstand compactive pressures better than those aggregates in treatments with very little soil cover.

Although some improvements in soil physical properties resulted from green manuring, the effect of these improvements on silage corn yield could not be readily determined. There were no significant treatment differences of total rotation yield, indicating that the green manures made some contribution to crop performance. As less than 50% of the variation in total rotation yield was explained by physical properties, it is likely that fertility factors were of greatest importance.

On the Franklin gravelly loamy sand, no treatment effects occurred in the measurement of any physical properties or soil organic carbon in the field. There were indications that buckwheat, incorporated on a regular basis, could improve aggregation and moisture retention in the long term. In a laboratory study, incorporated buckwheat proved able to aggregate more of the non-sand soil fraction than incorporated vetch. In the field, all three treatments that had buckwheat in the rotation had the highest moisture-holding capacity (though not significantly) at the end of the experiment.

In general, row cropping proved detrimental to the soil physical condition. Bulk density and the proportion of the soil aggregated were slightly reduced. In laboratory determinations, saturated hydraulic conductivity increased and moisture retention decreased with decreases in bulk density. It is likely that this occurred in the field as well and would affect negatively crop performance. Unfortunately, the large number of significant correlations between independent parameters made it impossible to determine cause-and-effect relationships between silage corn yield and soil physical properties.

For both soils, the determination of total soil organic carbon was inadequate to explain effects of treatments on soil physical properties. The measurement of the various components of organic matter, including polysaccharides and coarse organic material, would be better suited to this kind of study.

Three years would appear to be insufficient time to assess properly the impact of green manuring in a rotation on soil physical properties. It was not possible in three years to evaluate the persistence of effects or the implications of changes in the soil physical condition for crop performance. A study of this kind would require at least one more three-year cycle to determine if green manuring has benefits for crop production.

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APPENDIX. ABBREVIATED ANALYSIS OF VARIANCE TABLES

BEARBROOK CLAY

Bulk density

Sampling period: 1980

Source	df	Probability of > F planting	August	pre-harvest
Replicate (r)	2	0.3852	0.2475	0.7726
Treatment (trt)	7	0.5050	0.5275	0.6836
R*trt ($error_a$)	14			
Depth	3	0.0001	0.0001	0.0003
Trt*depth	21	0.1057	0.7530	0.4353
R*depth(trt) ($error_b$)	48			
$C.V._a$ (%)		7.55	10.58	8.57
$C.V._b$ (%)		5.01	6.50	5.76

Sampling period: 1981

Source	df	Probability of > F bc	August	post-harvest
Replicate (r)	2	0.6462	0.3966	0.5843
Treatment (trt)	7	0.0336	0.7345	0.6489
R*trt ($error_a$)	14			
Depth	3	0.0001	0.0008	0.0021
Trt*depth	21	0.0011	0.9838	0.5392
R*depth(trt) ($error_b$)	48			
$C.V._a$ (%)		8.71	10.09	10.21
$C.V._b$ (%)		4.12	9.68	7.35

Bulk density (cont.)

Sampling period: 1982

Source	df	pre-planting	August	post-harvest
		Probability of > F		
Replicate (r)	2	0.0642	0.2631	0.2608
Treatment (trt)	7	0.0073	0.3209	0.1006
R*trt ($error_a$)	14			
Depth	3	0.0001	0.0001	0.0001
Trt*depth	21	0.7877	0.0063	0.0523
R*depth(trt) ($error_b$)	48			
$C.V._a$ (%)		6.86	10.86	7.19
$C.V._b$ (%)		7.28	4.62	4.90

Sampling period: pre-cultivation, 1981. Analysis by depth.

Source	df	5 cm	10	15	20
		Probability of > F			
Replicate (r)	2	0.7894	0.8895	0.2620	0.4138
Treatment (trt)	7	0.1126	0.2726	0.0581	0.0001
R*trt (error)	14				
C.V. (%)		4.74	6.81	6.82	3.44

Sampling period: August, 1982. Analysis by depth.

Source	df	5 cm	10	15	20
		Probability of > F			
Replicate (r)	2	0.1805	0.4944	0.1342	0.7189
Treatment (trt)	7	0.3216	0.1257	0.1022	0.4931
R*trt (error)	14				
C.V. (%)		4.29	7.69	7.33	6.99

Bulk density (cont.)

Sampling period: post-harvest, 1982. Analysis by depth.

Source	df	Probability of > F: 5 cm	10	15	20
Replicate (r)	2	0.0064	0.2139	0.3224	0.6847
Treatment (trt)	7	0.0052	0.0470	0.2287	0.3162
R*trt (error)	14				
C.V. (%)		2.98	5.78	7.18	4.81

Sampling period: post-harvest compaction study, 1982.

Source	df	Probability of > F: 5 cm	10	15	20
Replicate (r)	2	0.8242	0.7848	0.7219	0.7707
Treatment (trt)	5	0.0251	0.3864	0.1110	0.8764
R*trt ($error_a$)	10				
Compaction (comp)	1	0.0001	0.0001	0.0001	0.0920
Comp*trt	5	0.2103	0.1726	0.3798	0.1496
R*comp(trt) ($error_b$)	12				
$C.V._a$ (%)		5.18	2.82	7.44	5.81
$C.V._b$ (%)		5.36	5.44	4.47	4.29

Sampling period: Compaction study, 1982. Differences between compacted and non-compacted rows at 5 cm.

Source	df	Probability of > F
Replicate (r)	2	0.0393
Treatment (trt)	5	0.0549
R*trt (error)	9	
C.V. (%)		41.10

Aggregation

Sampling period: planting, 1980

Source	df	Probability of > F dry	wet	%
Replicate (r)	2	0.0491	0.6262	0.3063
Treatment (trt)	7	0.1264	0.7322	0.5878
R*trt ($error_a$)	14			
Depth	1	0.3522	0.1023	0.4477
Trt*depth	7	0.4976	0.1885	0.7492
R*depth(trt) ($error_b$)	16			
$C.V._a$ (%)		8.61	9.44	9.52
$C.V._b$ (%)		5.93	6.43	7.00

Sampling period: August, 1980

Source	df	Probability of > F dry	wet	%
Replicate (r)	2	0.6603	0.0166	0.0843
Treatment (trt)	7	0.9120	0.4309	0.5826
R*trt ($error_a$)	14			
Depth	1	0.1530	0.3207	0.0189
Trt*depth	7	0.2668	0.1666	0.9361
R*depth(trt) ($error_b$)	16			
$C.V._a$ (%)		7.34	8.21	9.75
$C.V._b$ (%)		6.86	6.92	6.38

Aggregation (cont.)

Sampling period: August, 1981

Source	df	Probability of > F dry	wet	%
Replicate (r)	2	0.4845	0.0216	0.0259
Treatment (trt)	7	0.4791	0.0464	0.0854
R*trt ($error_a$)	14			
Depth	1	0.0018	0.9288	0.0012
Trt*depth	7	0.6895	0.8126	0.4133
R*depth(trt) ($error_b$)	16			
$C.V._a$ (%)		4.48	6.61	6.58
$C.V._b$ (%)		8.47	8.31	7.80

Sampling period: post-harvest, 1981

Source	df	Probability of > F dry	wet	%
Replicate (r)	2	0.6876	0.2938	0.2363
Treatment (trt)	7	0.1997	0.4280	0.2281
R*trt ($error_a$)	14			
Depth	1	0.0002	0.0971	0.0786
Trt*depth	7	0.1804	0.5508	0.1430
R*depth(trt) ($error_b$)	16			
$C.V._a$ (%)		7.46	9.02	6.74
$C.V._b$ (%)		4.60	7.72	5.83

Aggregation (cont.)

Sampling period: pre-planting, 1982

Source	df	Probability of > F dry	wet	%
Replicate (r)	2	0.6396	0.7271	0.6082
Treatment (trt)	7	0.6686	0.0070	0.0173
R*trt ($error_a$)	14			
Depth	1	0.0001	0.1234	0.0069
Trt*depth	7	0.5089	0.3361	0.8444
R*depth(trt) ($error_b$)	16			
$C.V._a$ (%)		9.64	7.25	8.16
$C.V._b$ (%)		6.69	8.26	7.80

Sampling period: post-harvest, 1982

Source	df	Probability of > F dry	wet	%
Replicate (r)	2	0.1279	0.0250	0.0024
Treatment (trt)	7	0.0188	0.8740	0.0048
R*trt ($error_a$)	14			
Depth	1	0.0001	0.0001	0.0001
Trt*depth	7	0.0728	0.5155	0.7472
R*depth(trt) ($error_b$)	16			
$C.V._a$ (%)		5.94	7.93	3.97
$C.V._b$ (%)		5.60	5.93	4.64

Aggregation (cont.)

Sampling period: N fertilizer study, post-harvest 1981

Source	df	Probability of > F WA	SA	LA
Replicate (r)	2	0.8775	0.9848	0.7513
Treatment (trt)	2	0.3436	0.4255	0.6764
R*trt ($error_a$)	4			
Fertilizer (fert)	3	0.7249	0.9433	0.9591
Trt*fert	6	0.9920	0.9868	0.8515
R*fert(trt) ($error_b$)	18			
Depth	1	0.0031	0.0017	0.0009
Trt*depth	2	0.2978	0.2800	0.7061
Fert*depth	3	0.3619	0.5663	0.1269
Trt*fert*depth	6	0.7303	0.8890	0.2512
R*depth(trt fert) ($error_c$)	24			
$C.V._a$ (%)		31.43	51.85	20.51
$C.V._b$ (%)		14.18	39.96	19.20
$C.V._c$ (%)		22.84	32.06	12.01

Sampling period: N fertilizer study, pre-planting 1982

Source	df	Probability of > F WA	SA	LA
Replicate (r)	2	0.6261	0.5279	0.5067
Treatment (trt)	2	0.8845	0.9004	0.9565
R*trt ($error_a$)	4			
Fertilizer (fert)	3	0.0057	0.0196	0.2076
Trt*fert	6	0.1066	0.5763	0.0748
R*fert(trt) ($error_b$)	18			
Depth	1	0.0001	0.0001	0.0001
Trt*depth	2	0.2665	0.6587	0.9467
Fert*depth	3	0.5962	0.6199	0.5752
Trt*fert*depth	6	0.1048	0.1611	0.1111
R*depth(trt fert) ($error_c$)	24			
$C.V._a$ (%)		21.84	31.13	41.73
$C.V._b$ (%)		9.28	16.88	18.44
$C.V._c$ (%)		11.68	19.89	20.97

Aggregation (cont.)

Sampling period: N fertilizer study, post-harvest 1982

Source	df	Probability of > F		
		WA	SA	LA
Replicate (r)	2	0.5379	0.9987	0.8922
Treatment (trt)	2	0.1306	0.3154	0.5965
R*trt ($error_a$)	4			
Fertilizer (fert)	3	0.6995	0.7664	0.9017
Trt*fert	6	0.1639	0.0283	0.0346
R*fert(trt) ($error_b$)	18			
Depth	1	0.0001	0.0001	0.0001
Trt*depth	2	0.2017	0.0160	0.0141
Fert*depth	3	0.4986	0.3344	0.5324
Trt*fert*depth	6	0.1909	0.2926	0.4159
R*depth(trt fert) ($error_c$)	24			
$C.V._a$ (%)		16.14	26.74	27.54
$C.V._b$ (%)		17.75	25.32	20.34
$C.V._c$ (%)		10.58	14.30	12.49

Soil organic carbon, pH, and calcium

Sampling period: 1980

Source	df	pH	OC	Ca
		Probability of > F		
Replicate (r)	2	0.8021	0.5351	0.9723
Treatment (trt)	7	0.2188	0.2064	0.2768
R*trt (error)	14			
C.V. (%)		5.00	9.11	11.36

Sampling period: 1981

Source	df	pH	OC	Ca
		Probability of > F		
Replicate (r)	2	0.1392	0.0064	0.0118
Treatment (trt)	7	0.2427	0.2254	0.6865
R*trt ($error_a$)	14			
Depth	1	0.1036	0.1973	0.6151
Trt*depth	7	0.6744	0.7695	0.2169
R*depth(trt) ($error_b$)	16			
$C.V._a$ (%)		5.74	13.46	34.69
$C.V._b$ (%)		4.90	10.44	33.30

Sampling period: post-harvest, 1982

Source	df	dry	wet	%
		Probability of > F		
Replicate (r)	2	0.7474	0.4082	0.9672
Treatment (trt)	7	0.6819	0.4438	0.8335
R*trt ($error_a$)	14			
Depth	1	0.6035	0.6642	1.0000
Trt*depth	7	0.8620	0.9812	0.4908
R*depth(trt) ($error_b$)	16			
$C.V._a$ (%)		6.40	23.18	23.57
$C.V._b$ (%)		3.35	18.68	6.47

Soil organic carbon, pH, and calcium (cont.)

Sampling period: Organic carbon, pre-planting and August, 1982

Source	df	Probability of > F pre-planting	Probability of > F August
Replicate (r)	2	0.3675	0.3872
Treatment (trt)	7	0.5346	0.2954
R*trt ($error_a$)	14		
Depth	1	0.1737	0.2570
Trt*depth	7	0.8049	0.5746
R*depth(trt) ($error_b$)	16		
$C.V._a$ (%)		18.28	19.55
$C.V._b$ (%)		11.56	12.48

Sampling period: N fertilizer study, post-harvest 1981

Source	df	Probability of > F pH	OC	Ca
Replicate (r)	2	0.1520	0.0192	0.0041
Treatment (trt)	2	0.3375	0.0062	0.0246
R*trt ($error_a$)	4			
Fertilizer (fert)	3	0.0083	0.0632	0.1109
Trt*fert	6	0.8227	0.7807	0.2204
R*fert(trt) ($error_b$)	18			
Depth	1	0.0089	0.4248	0.0148
Trt*depth	2	0.4689	0.0791	0.0379
Fert*depth	3	0.7407	0.7219	0.0233
Trt*fert*depth	6	0.5253	0.5895	0.7321
R*depth(trt fert) ($error_c$)	24			
$C.V._a$ (%)		9.53	5.66	19.09
$C.V._b$ (%)		8.55	13.49	38.30
$C.V._c$ (%)		4.67	12.27	43.19

Soil organic carbon, pH, and calcium (cont.)

Sampling period: N fertilizer study, organic carbon pre-planting 1982

Source	df	Probability of > F
Replicate (r)	2	0.2846
Treatment (trt)	2	0.4694
R*trt ($error_a$)	4	
Fertilizer (fert)	3	0.0046
Trt*fert	6	0.1043
R*fert(trt) ($error_b$)	18	
Depth	1	0.1560
Trt*depth	2	0.9178
Fert*depth	3	0.8856
Trt*fert*depth	6	0.8759
R*depth(trt fert) ($error_c$)	24	
$C.V._a$ (%)		16.85
$C.V._b$ (%)		6.94
$C.V._c$ (%)		12.63

Sampling period: N fertilizer study, post-harvest 1982

		Probability of > F		
Source	df	pH	OC	Ca
Replicate (r)	2	0.0628	0.2527	0.5263
Treatment (trt)	2	0.2260	0.0679	0.5808
R*trt ($error_a$)	4			
Fertilizer (fert)	3	0.1424	0.5637	0.5268
Trt*fert	6	0.3084	0.4990	0.7133
R*fert(trt) ($error_b$)	18			
Depth	1	0.4156	0.4484	0.0545
Trt*depth	2	0.4749	0.2691	0.4321
Fert*depth	3	0.6838	0.7563	0.5133
Trt*fert*depth	6	0.9402	0.6596	0.5620
R*depth(trt fert) ($error_c$)	24			
$C.V._a$ (%)		5.06	23.48	23.51
$C.V._b$ (%)		3.73	19.00	11.11
$C.V._c$ (%)		3.44	15.44	7.04

Moisture content and retention

Sampling period: Field moisture at each depth, post-harvest 1982

Source	df	Probability of > F 5 cm	10	15	20
Replicate (r)	2	0.0012	0.0001	0.0012	0.0408
Treatment (trt)	7	0.0062	0.0061	0.2370	0.9285
R*trt (error)	14				
C.V. (%)		9.15	5.46	6.18	8.44

Sampling period: 1980

Source	df	Probability of > F -0.10 bar	-1.0 bar	-15.0 bar	AWC.10
Rep (r)	2	0.4619	0.3407	0.4991	0.4118
Treatment (trt)	7	0.5918	0.8132	0.7649	0.4765
R*trt (error)	14				
C.V. (%)		7.62	7.94	4.90	27.03

Sampling period: 1981

Source	df	Probability of > F -0.10 bar
Rep (r)	2	0.0092
Treatment (trt)	7	0.2376
R*trt ($error_a$)	14	
Depth	1	0.0903
Depth*trt	7	0.0209
R*depth(trt) ($error_b$)	16	
$C.V._a$ (%)		6.93
$C.V._b$ (%)		5.75

Moisture content and retention (cont.)

Sampling period: pre-planting 1982

Source	df	Probability of > F			
		-0.10 bar	-1.0 bar	-15.0 bar	AWC.10
Rep (r)	2	0.6990		0.9018	0.5340
Treatment (trt)	7	0.6957		0.7405	0.5522
R*trt ($error_a$)	14				
Depth	1	0.0042		0.0231	0.0525
Depth*trt	7	0.0662		0.2382	0.1964
R*depth(trt) ($error_b$)	16				
$C.V._a$ (%)		8.89		6.17	28.58
$C.V._b$ (%)		5.64		4.82	19.92

Sampling period: post-harvest 1982

Source	df	Probability of > F			
		-0.10 bar	-1.0 bar	-15.0 bar	AWC.10
Rep (r)	2	0.0244	0.0185	0.0040	0.4209
Treatment (trt)	7	0.7789	0.7064	0.1567	0.9832
R*trt ($error_a$)	14				
Depth	1	0.0009	0.0001	0.0553	0.0016
Depth*trt	7	0.5662	0.2923	0.7514	0.6552
R*depth(trt) ($error_b$)	16				
$C.V._a$ (%)		6.60	7.25	3.92	31.00
$C.V._b$ (%)		5.68	5.35	4.17	22.57

Water flow

Friedman's 2-way analysis of variance

Sampling period: Ksat 1980.

Rep	Treatment							
	A	B	C	D	E	F	G	H
1	3	7	4	1	2	8	6	5
2	8	1	2	6	7	4	5	3
3	4	3	5	7	2	6	8	1
Total	15	11	11	14	11	18	19	9

$\chi_r^2 = 5.11$

Sampling period: Infiltration time at 2 cm added, pre-cultivation 1982

Rep	Treatment							
	A	B	C	D	E	F	G	H
1	1	8	5	6	2	7	3	4
2	5	1	4	8	7	6	3	2
3	3	6	4	2	8	7	5	1
Total	9	15	13	16	17	20	11	7

$\chi_r^2 = 7.33$

Sampling period: Infiltration time at 4 cm added, pre-cultivation 1982

Rep	Treatment							
	A	B	C	D	E	F	G	H
1	1	8	4	5	3	7	2	6
2	5	1	7	6	4	3	8	2
3	5	8	2	1	7	3	6	4
Total	11	17	13	12	14	13	16	12

$\chi_r^2 = 1.67$

Water flow (cont.)

Sampling period: Infiltration time at 4 cm added, post-harvest 1982

Rep	Treatment							
	A	B	C	D	E	F	G	H
1	3	5	2	8	4	7	6	1
2	8	6	1	7	5	4	2	3
3	3	7	5	2	4	8	1	6
Total	14	18	8	17	13	19	9	10

$X_r^2 = 7.00$

Sampling period: Infiltration time at 6 cm added, post-harvest 1982

Rep	Treatment							
	A	B	C	D	E	F	G	H
1	2	5	3	8	4	7	6	1
2	8	6	1	7	4	3	5	2
3	7	6	3	1	4	8	2	5
Total	17	17	7	16	12	18	13	8

$X_r^2 = 7.00$

Crop yield

Sampling period: Total rotation yield

Source	df	Probability of > F
Year (yr)	2	0.0126
Replicate (r)	2	0.0407
Yr*r ($error_a$)	4	
Treatment (trt)	7	0.1215
Trt*yr	14	0.0001
R*trt(yr) ($error_b$)	36	
$C.V._a$ (%)		15.91
$C.V._b$ (%)		26.30

Sampling period: N fertilizer study, 1981

Source	df	Probability of > F
Replicate (r)	2	>0.1000
Treatment (trt)	2	>0.1000
R*trt ($error_a$)	4	
Fertilizer (fert)	3	0.0001
Fert*trt	6	>0.1000
R*fert(trt) ($error_b$)	18	
$C.V._a$ (%)		51.36
$C.V._b$ (%)		22.03

Sampling period: N fertilizer study, 1982

Source	df	Probability of > F
Replicate (r)	2	0.0669
Treatment (trt)	4	0.0929
R*trt ($error_a$)	6	
Fertilizer (fert)	3	0.0017
Fert*trt	12	0.5387
R*fert(trt) ($error_b$)	11	
$C.V._a$ (%)		27.32
$C.V._b$ (%)		27.12

FRANKLIN GRAVELLY LOAMY SAND

Bulk density

Sampling period: 1980

Source	df	Probability of > F: pre-cultivation	August
Replicate (r)	2	0.3995	0.8354
Treatment (trt)	7	0.0533	0.1654
R*trt ($error_a$)	14		
Depth	3	0.0444	0.1473
Trt*depth	21	0.5422	0.5515
R*depth(trt) ($error_b$)	48		
$C.V._a$ (%)		7.29	8.93
$C.V._b$ (%)		7.83	8.02

Sampling period: 1981

Source	df	Probability of > F: pre-cultivation	July	post-harvest
Replicate (r)	2	0.4650	0.8255	0.1122
Treatment (trt)	7	0.9356	0.9070	0.8019
R*trt ($error_a$)	14			
Depth	3	0.0128	0.0001	0.1922
Trt*depth	21	0.1083	0.3106	0.5087
R*depth(trt) ($error_b$)	48			
$C.V._a$ (%)		9.56	14.04	9.53
$C.V._b$ (%)		7.29	11.24	7.75

Bulk density (cont.)

Sampling period: 1982

Source	df	Probability of > F pre-planting	Probability of > F post-harvest
Replicate (r)	2	0.0157	0.8454
Treatment (trt)	7	0.5243	0.3346
R*trt ($error_a$)	14		
Depth	3	0.1836	0.0001
Trt*depth	21	0.1889	0.1067
R*depth(trt) ($error_b$)	48		
$C.V._a$ (%)		9.97	8.58
$C.V._b$ (%)		8.71	5.96

Aggregation

Sampling period: 1980

Source	df	Probability of > F pre-cultivation	August	post-harvest
Replicate (r)	2	0.0528	0.0492	0.0398
Treatment (trt)	7	0.7474	0.6358	0.5154
R*trt ($error_a$)	14			
Depth	1	0.4057	0.0001	0.0966
Trt*depth	7	0.9241	0.4755	0.6088
R*depth(trt) ($error_b$)	16			
$C.V._a$ (%)		38.49	33.41	21.66
$C.V._b$ (%)		24.52	15.22	14.03

Sampling period: 1981

Source	df	Probability of > F pre-cultivation	July	pre-harvest
Replicate (r)	2	0.2256	0.0060	0.0187
Treatment (trt)	7	0.4294	0.0956	0.6123
R*trt ($error_a$)	14			
Depth	1	0.0002	0.0001	0.0001
Trt*depth	7	0.8833	0.6582	0.9364
R*depth(trt) ($error_b$)	16			
$C.V._a$ (%)		23.80	23.54	25.99
$C.V._b$ (%)		22.66	19.28	14.35

Aggregation (cont.)

Sampling period: 1982

		Probability of > F	
Source	df	pre-planting	post-harvest
Replicate (r)	2	0.7727	0.1233
Treatment (trt)	7	0.4866	0.4413
R*trt ($error_a$)	14		
Depth	1	0.0062	0.0001
Trt*depth	7	0.8998	0.3239
R*depth(trt) ($error_b$)	16		
$C.V._a$ (%)		28.78	30.68
$C.V._b$ (%)		24.17	13.34

Sampling period: N fertilizer study 1981 and 1982

		Probability of > F	
Source	df	pre-harvest 81	pre-planting 82
Replicate (r)	2	0.6483	0.1274
Fertilizer (fert)	2	0.5210	0.4825
R*fert ($error_a$)	4		
Depth	1	0.0092	0.2198
Fert*depth	2	0.2110	0.6047
R*depth(fert) ($error_b$)	6		
$C.V._a$ (%)		15.52	14.81
$C.V._b$ (%)		10.52	25.99

Aggregation (cont.)

Sampling period: N fertilizer study, post-harvest 1982

Source	df	Probability of > F post-harvest 82
Replicate (r)	2	0.0990
Treatment (trt)	4	0.2112
R*trt ($error_a$)	8	
Fertilizer (fert)	2	0.4918
Trt*fert	8	0.7605
R*fert(trt) ($error_b$)	20	
Depth	1	0.0001
Trt*depth	4	0.1219
Fert*depth	2	0.0858
Trt*fert*depth	8	0.6277
R*depth(trt fert) ($error_c$)	24	
$C.V._a$ (%)		46.27
$C.V._b$ (%)		24.83
$C.V._c$ (%)		15.60

Soil organic carbon, pH, and calcium

Sampling period: 1980

Source	df	pH	OC	Ca
		Probability of > F		
Replicate (r)	2	0.0126	0.4393	0.5694
Treatment (trt)	7	0.0415	0.6009	0.3397
R*trt (error)	14			
C.V. (%)		4.74	33.52	20.68

Sampling period: 1981

Source	df	pH	OC	Ca
		Probability of > F		
Replicate (r)	2	0.0478	0.5069	0.5758
Treatment (trt)	7	0.2998	0.6035	0.2996
R*trt ($error_a$)	14			
Depth	1	0.0001	0.8771	0.0001
Trt*depth	7	0.1761	0.5269	0.2129
R*depth(trt) ($error_b$)	16			
$C.V._a$ (%)		8.59	22.33	38.33
$C.V._b$ (%)		3.68	15.39	28.87

Soil organic carbon, pH, and calcium (cont.)

Sampling period: post-harvest, 1982

Source	df	pH	OC	Ca
		Probability of > F		
Replicate (r)	2	0.5392	0.0329	1.0000
Treatment (trt)	7	0.6336	0.4258	0.3349
R*trt ($error_a$)	14			
Depth	1	0.0371	0.7323	0.4382
Trt*depth	7	0.0075	0.0930	0.3587
R*depth(trt) ($error_b$)	16			
$C.V._a$ (%)		5.51	28.39	30.15
$C.V._b$ (%)		2.70	18.48	13.16

Sampling period: N fertilizer study, post-harvest 1982

Source	df	pH	OC	Ca
		Probability of > F		
Replicate (r)	2	0.8499	0.1712	0.2146
Treatment (trt)	4	0.9384	0.7920	0.5136
R*trt ($error_a$)	8			
Fertilizer (fert)	2	0.6443	0.1698	0.7430
Trt*fert	8	0.2936	0.3801	0.0694
R*fert(trt) ($error_b$)	20			
Depth	1	0.0001	0.0547	0.0076
Trt*depth	4	0.1494	0.0412	0.2428
Fert*depth	2	0.6104	0.1466	0.2166
Trt*fert*depth	8	0.4452	0.6693	0.9056
R*depth(trt fert) ($error_c$)	24			
$C.V._a$ (%)		5.64	44.02	41.12
$C.V._b$ (%)		5.09	23.39	21.28
$C.V._c$ (%)		2.78	21.62	15.97

Laboratory experiment

Source	df	Probability of > F			
		Aggregation	pH	Organic carbon	Calcium
Pl	1	0.0001	0.0001	0.0575	0.0023
Pr	2	0.3563	0.0270	0.7080	0.8522
Trt	5	0.0450	0.1577	0.7820	0.3809
Pl*Pr	2	0.4825	0.0004	0.7345	0.7167
Pl*trt	5	0.2782	0.0305	0.4825	0.6900
Pr*trt	10	0.7875	0.0172	0.2328	0.9909
Pl*Pr*trt	10	0.5678	0.5008	0.6535	0.2996
R(Pl Pr trt)	36				
C.V. (%)		15.32	1.47	15.13	12.55

Moisture retention

Sampling period: 1980

		Probability of > F			
Source	df	-0.10 bar	-0.33 bar	-15.0 bar	AWC.10
Rep (r)	2	0.1715	0.0828	0.0347	0.4461
Treatment (trt)	7	0.9436	0.8901	0.9929	0.6455
R*trt (error)	13				
C.V. (%)		17.87	17.52	19.37	23.06

Sampling period: 1981

		Probability of > F			
Source	df	-0.10 bar	-0.33 bar	-15.0 bar	AWC.10
Rep (r)	2	0.0537		0.1376	0.6444
Treatment (trt)	7	0.7905		0.8787	0.6735
R*trt (error)	14	0.0001		0.0001	0.0001
S(r*trt)	48				
C.V. (%)		19.61		25.95	31.20

Moisture retention (cont.)

Sampling period: pre-planting, 1982

Source	df	Probability of > F			
		-0.10 bar	-0.33 bar	-15.0 bar	AWC.10
Rep (r)	2	0.0772	0.0833	0.1405	0.2111
Treatment (trt)	7	0.8572	0.9517	0.7636	0.8975
R*trt (error)	14	0.0001	0.0001	0.0001	0.0001
S(r*trt)	48				
C.V. (%)		22.09	23.89	27.12	29.90

Sampling period: post-harvest, 1982

Source	df	Probability of > F			
		-0.10 bar	-0.33	-15.0 bar	AWC.10
Rep (r)	2	0.0516	0.0656	0.0327	0.4823
Treatment (trt)	7	0.4067	0.7335	0.5102	0.3542
R*trt (error)	14	0.0001	0.0001	0.0001	0.0001
S(r*trt)	48				
C.V. (%)		20.99	22.89	22.81	32.73

Saturated hydraulic conductivity

Source	df	1980	1981	bpl 1982	ph 1982
		Probability of > F*			
Rep (r)	2	0.0760	0.0044	0.1272	0.2852
Treatment (trt)	7	0.4877	0.7806	0.1760	0.8885
R*trt (error)	14	0.0001	0.0001	0.0001	0.0001
S(r*trt)	48				
C.V. (%)		46.07	37.19	3.19	41.83

* Analysis performed on log base 10 values

Corn yield

Sampling period: Total rotation yield

Source	df	Probability of > F
Year (yr)	2	0.0001
Replicate (r)	2	0.9837
Yr*r ($error_a$)	4	
Treatment (trt)	7	0.0001
Trt*yr	14	0.0001
R*trt(yr) ($error_b$)	42	
$C.V._a$ (%)		20.81
$C.V._b$ (%)		27.21

Sampling period: N fertilizer study, 1981

Source	df	Probability of > F
Replicate (r)	2	>0.1000
Treatment (trt)	2	0.1000
R*trt (error)	4	
C.V. (%)		9.51

Sampling period: N fertilizer study, 1982

Source	df	Probability of > F
Replicate (r)	2	0.4071
Treatment (trt)	4	0.3714
R*trt ($error_a$)	8	
Fertilizer (fert)	2	0.2208
Fert*trt	8	0.5458
R*fert(trt) ($error_b$)	20	
$C.V._a$ (%)		91.49
$C.V._b$ (%)		30.34