PART II.

CLIMATIC CHANGE and SOIL PROCESSES.

Introduction

This part is concerned with the potential impact of global warming on many processes which occur in soil that are important to agriculture and the environment in general. We discuss the effects of increased atmospheric [CO_2] and air temperature, and of changes in precipitation patterns, on the extents to which physical and chemical properties of soils would be changed. The implications of such changes for soil structure and microbial activity are then reviewed in the context, primarily, of nutrient cycling.

It will become clear that the many interactions between different processes, and in some cases the uncertainties of measuring certain processes, mean that predictions of events on a local scale are necessarily less reliable than those for global weather patterns (see Part I).

II. 1. Effects of climatic change on physical structure and acidity of soil.

The simplicity of the term 'soil' belies the variability and complexity of the medium. In this Section, terms such as clay, silt and sand are used to give a more precise description of specific soil characteristics. These subclassifications are necessary to provide a basis from which to explain the many and complex processes which occur in the soil. However, it is worth emphasising the wide range of soil types which exist within these subclassifications. For instance, the USDA (1975) have over 230 groups of soil which are further subdivided into three levels of categorisation. In 1970, 10000 soil series were identified in the USA (Soil Survey, 1973). The variability of soil types is emphasised by FitzPatrick (1983) who classifies soils according to individual horizons. In fact this author notes that as "soils are composed of horizons and as a whole form continua in space and time they defy classification!". The great diversity of soil types is matched by the diversity in their response to a changing climate.

(a) Temperature effects.

Soil temperature depends ultimately on the solar radiation flux incident on its surface. Altitude, latitude, slope and aspect of the land, the soil's water content and vegetation cover, and the cloud cover, are all factors that influence this flux (see. e.g. Rorison *et al.*, 1986). Generally, temperature fluctuations in soil beneath vegetation are less than those of bare soil, and fluctuations are expected to remain similar to those at present. Theories exist for predicting bare soil temperature (e.g. Buchan, 1982) but not for vegetated soil, although both are of relevance to agriculture.

The thermal buffering properties of soil mean that temperatures close to the soil surface are similar to those of the atmosphere. Fluctuations are damped with depth in the soil, disappearing altogether below a critical depth which varies from place to place (Campbell, 1977; Milthorpe & Moorby, 1979), but long-term increases in temperature will not be buffered. This has important implications for the frequency of freeze-thaw (see Section II.1(c)).

(b) CO_2 effects.

$[CO_2]$ in soils is generally considerably higher than in the above-ground atmosphere, due to microbial and plant root respiration which generates CO_2, and to the tortuosity of diffusion pathways between sites of respiratory activity and the soil surface (Rowell, 1988). $[CO_2]$ generally can range from 1 to 5% (by volume) of the soil air but values as high as 14% have been recorded in carbon (C)-rich substrates. Any increases in respiration caused by an increase in atmospheric $[CO_2]$ are unlikely to have significant effects on this high background of $[CO_2]$ in soil. For this reason, soil pH, which is related to $[CO_2]$ in the soil air and which influences the entire chemistry of the soil solution, is unlikely to change significantly as a direct result of an increase in atmospheric $[CO_2]$.

(c) Soil Structure.

An adequate soil structure is vital for healthy plants. A suitable structure must be one that is sufficiently loose and open to allow good aeration and easy root growth, as well as having sufficient strength to withstand heavy agricultural traffic.

The presence of organic matter in soils helps stabilise structural pores. Where intensive cultivations reduce organic matter levels (Rovira & Greacon, 1957) structural degradation (i.e. loss of porosity and discrete structural units) may occur, and unless corrected may have disasterous consequences for agriculture. As stated in Section II.2, the onset of climatic change and the resultant change in soil moisture conditions, rather than temperature, will have a controlling influence on soil organic matter decomposition. Therefore, structural degradation through increased organic matter decomposition may accelerate. At present, it is estimated that the global annual loss of land to soil degradation is between 5 and 7 million hectares (UNEP, 1986); and soil degradation affects 35% of the Earth's surface (Mabbutt, 1984). It has also been estimated (Anderson, 1989) that land degradation and related processes cost Australia $A 600 million a year in lost agricultural production. It is clearly a significant problem.

Structural difficulties occur in a wide range of soil types - even soils with loamy textures which have traditionally been seen as the best mineral soils, in terms of both chemical and physical fertility. In such soils under intensive management systems, there is a progressive degradation of soil structure. Although increasing fertiliser application and irrigation can sometimes compensate for, or mask the problems associated with poor root development in such degraded soils, this merely delays the manifestation of serious soil physical problems. The concern voiced by the Agricultural Advisory Council (1970) that "weak soil structure was one of the major problems of the agricultural industry" has not diminished. Although at present the problem is more severe in the tropics, the processes involved in degradation are similar in all regions (Lal, 1989). While it is clear that massive degradation as is occuring in the Sahel region will not occur here, subtle changes in organic matter levels may lead to severe physical problems. Young *et al.* (1988) clearly showed the effects of structural degradation on crop growth on two U.K. soils (Wick series) at the Institute of Horticultural Research, Wellesbourne. These soils had organic matter levels of around 2%.

No matter how sophisticated the agricultural techniques, the soil must be in a fit condition to support traffic for ploughing, sowing, spraying and harvesting. Otherwise, the soil could be damaged (e.g. compacted) by traffic. Consequently the crop will suffer as a result of late planting or harvesting or if the soil is ploughed or sown when too wet or dry, leading to soil physical conditions harmful to crop growth. Many farmers consistently over-estimate the soil's load-bearing capacity (the load/force that the soil can support without being excessively damaged) causing damage in the topsoil and subsoil by untimely traffic or cultivation. Recently, such damage has been exacerbated by the use of heavy machinery and the management of soils under conditions ill-suited to cultivations. Although farm animals and machines do not necessarily cause compaction on wet land, they can leave once aggregated soil in a puddled condition (Gradwell, 1966) and damage soil structure. Again, the effect varies on different soil types. Most sandy soils drain quickly and have enough strength at field capacity to withstand traffic. Clay soils, however, drain more slowly (see above) and cannot endure the weight of agricultural machinery without sustaining damage to the soil's structure.

Timeliness of tillage operations then become vital. Even if AAP were to decrease significantly it could still be difficult to create an adequate seed-bed since at too low a moisture content aggregates no longer exhibit adequate friability (i.e. ease of aggregate breakdown) (Young, 1987). Such a seed-bed would be too cloddy for plant establishment. Economic pressures force farmers to get crops on and off the land as fast as possible, pressures which may increase if the predicted AAP changes are correct. In the long-term this will undoubtedly mean degradation of the soil's structure leading to lower yields. McGarry (1989) examined the effect of cultivating a vertisol under wet and dry conditions. It was found that wet cultivations increased the zones of stratified clay within the soil: the wet treatment had approximately 17% of its area composed of strongly stratified clay, whereas for the dry treatment under 1% of the area was composed of clay. Such an increase in clay stratification led to the wet cultivated soil having a more apedal structure than the more aggregated structure seen in the dry treatment. The processes which led to the increases in stratification are as yet unknown and deserve more attention.

The natural weathering processes of wet-dry and freeze-thaw cycles are among the most important mechanisms for the generation of structure within the soil profile. Such structural development is termed 'self-mulching', and is particularly evident within the vertisol group (Soil Survey Staff, 1975). Alternate wet-dry cycles cause shrinkage and swelling stresses in the soil, resulting in the weakening and fracture of large clods/aggregates into smaller units. Clay soils are more susceptible to such weathering than loams or silts. Periods of freezing and thawing act in a similar fashion. By cultivating in autumn a farmer can take advantage of weathering cycles to improve or maintain soil structure. Successive simulated wet-dry cycles in laboratory experiments decrease aggregate size, the rate of decrease declining with aggregate size (Sheil *et al.*, 1988). Simulated wet-dry cycles are, however, usually more severe and rapid than those occurring in the field.

In drier climates, periods of wetting and drying can cause deep cracks in the profile, aiding water and root penetration to depth - especially important in clay soils. However, the present climate in the U.K. is not sufficiently dry to allow this to occur, and only a surface mulch should form. If AAP decreases uniformly, natural weathering processes may cause deep cracks in the soil, although the picture is more complicated than this. A drier, warmer climate would decrease freeze-thaw cycles as well as permit drier conditions in the soil profile. Soils in the U.K. benefit considerably from periods of frost prior to sowing for structural generation. The advantages and disadvantages of changes in AAP and temperature to structural generation in the U.K. are poorly understood and demand further attention. Priorities for related research are outlined at the end of this part.

The small predicted increase in air temperature may extend the growing season in the U.K. by a few weeks (Rowntree *et al.*, 1989). However, winter rainfall will dictate whether the farmer is able to make use of this extension since the prevailing soil moisture conditions in winter or early spring control the timing of spring cultivations (see later). Unfortunately, as explained in Part I, no reliable predictions of changes in precipitation patterns in the U.K. are presently available.

The general effect of any changes in soil moisture conditions will vary according to soil type. Any increase in average annual precipitation (AAP) would have most impact on the clay which drains more slowly than the others because of its narrower pores, and which would take longer to reach field capacity than the more freely draining sand. Clay soils represent over 40% of the main cereal growing areas in the U.K. (AFRC. 1988). If AAP increases, drainage must be made more efficient: one estimate suggests that 50% of land drains in the U.K. operate sub-optimally (T.E. Batey, private communication). This will require agricultural engineering expertise, either to develop more efficient systems, or to encourage more widespread, efficient use of existing systems.

If AAP decreases, irrigation must be increased or introduced, particularly during early vegetative growth when crops are most susceptible to drought. A more scientifically-based approach to the timing of irrigation may help to offset some of the extra costs of irrigating. The availability of cheap, portable tensiometers (Mullins *et al.*, 1987) to record soil water potentials at and below rooting depth, together with a better understanding of soil moisture processes, would give the farmer more information with which to schedule irrigation. Possible changes in drainage patterns must be recognised by the farmer: the model of Rowntree *et al.* (1989), for example, shows that a uniform decrease in AAP of 20% would mean that some soils might not return to field capacity at all, and that irrigation up to cultivation would be needed.

(d) Upland Soils.

In terms of their chemistry, biology and associated vegetation, upland soils are very different from their lowland counterparts used for intensive agriculture. These differences result partly from climatic factors. Air temperatures decline by *c.* 7 +/- 1 C° per km rise in altitude, evapotranspiration rates usually decline and windspeeds increase with altitude (Grace, 1987). One important net result of these factors is a buildup of soil organic matter which decomposes relatively slowly. Decomposition is further retarded by acid conditions which result from the leaching of exchangeable ions from the soil during heavy rainfall. Many upland plant communities in the U.K. are dominated by slow growing, unproductive, acid tolerant perennials.

An increase in air temperature of 2C° is equivalent to an effective "lowering of" altitude by *c.* 300m. If maintained, such a temperature increase would allow the gradual incursion of trees for example, onto soils currently above the tree line. However, this tendancy could be offset to some extent by the prevailing high windspeeds at altitudes which are inimical to the growth of tall plants. This is presently the most dramatic vegetation change which could occur on upland soils, and it could open up greater areas of land for timber production than are presently available.

Another vegetation change which could occur is the conversion of unproductive heathland into grass/clover dominated pasture. While such plants could be encouraged to grow at higher altitudes under a warmer climate, this will occur only through considerable inputs of fertilizers and lime to increase soil pH. Economic factors will decide whether this is a realistic possibility or not; the same applies for timber production.

Should global warming mean that extensive tracts of upland will become *potentially* available for agricultural exploitation (for pasture, timber, agroforestry, etc.) a dilemna will be created: to make use of this agricultural opportunity, or to conserve for amenity purposes hitherto "unspoilt" moorland and heath? Such policy decisions will be helped if appropriate data could be obtained on the extent of the areas of upland which could potentially become economically viable for certain types of agriculture.

These positive aspects of global warming need, however, to be balanced against some negative ones. Warmer temperatures could mean decomposition rates of a magnitude insignificant in lowland, intensive agricultural soils, but sufficiently large to have an impact in uplands. If rates of decomposition do increase, a breakdown in the soil's structural stability is possible which eventually would lead to the problems detailed in section (c) above. This is being seen already in lowland peat soils that have been drained (Young, 1989). Clearly any management options for upland conditions should be sensitive to such adverse possibilities.

(e) Summary.

In summary, it has been suggested that predicted increases in [CO_2] concentrations and temperature will have little effect on crop performance, and that the resultant soil moisture conditions will be of the greatest importance. Even where a small rise in temperature may lengthen the growing season, the soil moisture conditions would control whether or not the farmer is able to cultivate etc., without damaging the soil structure. It has been shown that particle size distribution will have a controlling influence on the soil's ability to cope with an increase in AAP.

Timeliness of cultivations and other tillage practices will increase in importance if AAP increases or precipitation distribution is altered. A less empirical approach to management strategies is called for in the light of the predicted climatic changes.

The alteration of AAP will have important consequences for the wetting-drying and freezing-thawing cycles which are essential for the maintenance of soil structure. At present little quantitative knowledge is available concerning the response of these natural weathering processes to changes in AAP.

II.2. Effects of Climatic Change on Soil Microbiology.

(a) Decomposition.

Macroclimatic conditions, primarily temperature and rainfall, exert a dominant influence on the amounts of organic matter found in soils. In general, progression from cold to warm, and from dry to wet, climates results in a decrease in soil carbon content and a wider range of carbon:nitrogen (C:N) ratios (Brady, 1974). Decomposition of soil organic matter and the allied cycling of nutrients are processes carried out predominantly by the myriad of soil organisms (bacteria, fungi, actinomycetes, micro- and meso-fauna) whose activity is governed ultimately by the prevailing climate. Whilst temperature and soil water potential are important regulators at both macro and micro scales, substrate quality, concentrations of CO_2 and O_2, soil texture, structure, inorganic nutrient status and the structure of microbial populations will all influence net decomposition at a local level.

Rates of decomposition and nutrient mineralisation increase with temperature between lower and upper limits (cardinal points) and show optima which tend toward the upper point. Whilst Q_{10} (the proportional response of a rate process elicited by at 10C° rise in temperature) is often assumed to be about 2.0, but this is rarely the case for decomposition in soil as the processes are not the result of a single chemical reaction, but of many interacting biological and physiological mechanisms, all of which have different responses to temperature. Ammonification (the production of ammonium-N from organic-N) is unusual among soil processes in that the temperature optimum is in the thermophilic (45 to 60°C), rather than mesophilic, range (Alexander, 1977). Modest temperature increases would accelerate decomposition rates but would not affect significantly the final extent of decomposition. An increase of 1 or 2C° in average soil temperature would, therefore, have little direct effect other than to increase decomposition and nutrient cycling rates slightly. Consideration of temperature effects in isolation are, however, naive because of the plethora of modifying factors (especially soil water status) which can dominate any simple temperature effect.

Soil water potential exerts a major influence on decomposition rates, and this has been studied extensively (see Harris, 1980). In general, decomposition is inhibited by low and high water potentials, but does not cease entirely in very wet soils. In dry soils, microbes become water-limited, and under wet conditions biological activity is decreased by lack of O_2 which diffuses considerably more slowly in aqueous than gaseous phases of soil. Differential responses to water potential by various groups of soil organisms are much more pronounced than responses to temperature. Eucarpic fungi are tolerant of low water potential, showing activity in soils down to -15 MPa, whilst bacterial activity is curtailed at -1.5 MPa or higher (Swift *et al.*, 1979). This is because bacteria rely on mobility in water films to gain access to substrates, whilst the hyphal growth form of many fungi permits them to explore new zones of soil for substrates more independently of soil water films. Generally, microbial activity in soils starts to be limited significantly at water potentials below -1 to -5 MPa. Interactions between temperature and moisture have often been reported. Clark & Gilmour (1983), for example, found that the influence of temperature on the rate constant for decomposition was much smaller under saturated than unsaturated conditions.

Decomposition is influenced also by cycles of temperature and moisture regimes, especially where cardinal boundaries are crossed, as in freeze-thaw and wet-dry cycles (e.g. Ivarson & Sowden, 1970; Kieft *et al.*, 1987). Such cycles influence both substrate quality, primarily through physical disruption (see Section II.1(c)), and microbial populations which show high mortality rates following freezing or drying. Cyclic changes generally cause flushes of C and N mineralisation, with successive cycles causing slightly smaller flushes (Campbell & Biederbeck, 1982; Orchard & Cook, 1983).

In summary, wetter climates would tend to enhance decomposition in well-drained soils; prolonged waterlogging would depress decomposition markedly. Any effect of drier summers limiting decomposition would probably be offset by enhanced decomposition if winters were warmer and wetter, but drier winters may result in significantly less decomposition.

Studies on the effects of [CO_2] on decomposition are few and difficult to interpret since many have not considered pH effects (see Section II. 1(b)). There is some evidence that fungi may be stimulated by high [CO_2] and that the bicarbonate ion concentration is of most significance to fungal growth (Griffin, 1972). Bicarbonate is present in aqueous solution in insignificant amounts below pH6.0 and, consequently, responses to [CO_2] both in soil and atmosphere might be expected to be greater in alkaline soils.

If climatic conditions change such that decomposition is enhanced, evolution of CO_2 from soils will show a concomitant increase. Proportions of organic C lost from newly-incorporated substrates will be broadly similar (40 to 60% within a few years), but the loss will be more rapid. Over the long term, decomposition of native soil C, i.e. that which has accumulated under existing climatic regimes, will also be increased. Whether this will be a significant net loss depends on the rate of organic C *inputs* (ultimately from photosynthesis) which will result from the modified climate. The concentrations of CO_2, and its ionic dissociates, in the soil environment will be increased by greater respiratory production from roots and microorganisms. Thus the soil will not act as a sink for any of the increased CO_2 in the above soil atmosphere. The consequences of this increased soil [CO_2] on the autotrophic fixation of carbon in the soil, are not clear.

Multivariate analysis techniques have demonstrated the close correlation between climate and soil C content (Jenny, 1961), decomposition rates (Heal & French, 1974) and soil microbial biomass (Inram *et al.*, 1989). In all these studies, the strongest predictors were variates incorporating water and temperature factors. In the latter study, the best predictor of biomass C was a precipitation-evaporation quotient which integrates rainfall and temperature parameters. Correlation was greater if biomass C was expressed on the basis of soil C. The 87 North American soils (12 soils with different cropping histories) in their study were at equilibrium and this approach is important in that it has enabled the generation of an equilibrium function relating microbial C/soil C to precipitation/evaporation. Deviations from this function would indicate whether a certain soil is losing or accumulating organic matter, an important question given the likely effects of climatic change on microbial processes in soils. Unfortunately, the predictive value of the equilibrium function was better for arid-zone soils than for humid-zone ones, but the approach shows potential and is worthy of further investigation.

(b) Nitrogen Transformations.

Any increase in the amounts of ammonium-N released during the decomposition of soil organic matter (see above) stimulated by a 1 or 2C° rise in temperature, will be liable to conversion to nitrate-N via nitrification. Nitrification is an autotrophic process and so is not controlled by the availability of C substrates. It is, however, affected by plant development. The rate of nitrifier activity is greatest early in the season during the first stages of development of the root system. Recent work also suggests that it is most active during periods of optimal microbial activity and results in significant losses of N as nitrous oxide (N_2O) by nitrate respiration (Wheatley, unpublished results).

The nitrate-N formed during nitrification is liable to dissimilatory reduction by bacteria or to loss by leaching. One route of dissimilatory reduction is denitrification, during which nitrate-N is reduced to gaseous forms, i.e. N_2O and molecular nitrogen, N_2, which are lost from the soil to the atmosphere. The balance between N_2 and N_2O production is especially important in the context of global warming since the latter gas absorbs radiation in the wavelength range 8 to 12 µm (Section I.1). Quantifying the contribution made to increases in atmospheric $[N_2O]$ by denitrification products is difficult because of the lack of reliable methods to measure fluxes in the field (Ryden & Ralston, 1987) and because of the large spatial variability of the process. The combination of effects resulting from a warmer, longer growing season in the U.K. may increase losses of N from soils, provided that the other necessary conditions (anoxia and C-substrate availability) for denitrification also occur at the same time. The alternative route of dissimilatory nitrate reduction, in which nitrate-N is reduced to ammonium-N, may well be controlled by slightly different factors. The balance between the two routes of nitrate loss may change under different climates.

Moisture has a profound effect on these processes, and changes in rainfall patterns might be more important than temperature in this context. Frequent but intermittent rainfall during periods of active nitrification may lead to significant losses of N_2O since the resulting O_2 limitation will promote nitrite respiration. Continuous rain during this time resulting in waterlogging and anoxia will prevent both mineralisation and nitrification. Periods of heavy rain following nitrification will cause heavy losses of nitrate through denitrification in poorly-drained soils or leaching in freely-draining soils.

Increased atmospheric $[CO_2]$ might have a direct effect on soil N transformations through greater losses of C substrates from plant roots, but the likely extents of such effects are unknown.

(c) Soil invertebrates.

Larger invertebrates (e.g. earthworms, woodlice, multipedes) are important for the initial communication and incorporation of organic matter. Smaller invertebrates (e.g. collembola, mites, nematodes and protozoa) are regulators of bacterial and fungal activity and stimulate C, N and phosphorus (P) mineralisation. The metabolism of soil invertebrates is affected by temperature such that rates of ingestion, digestion, excretion, growth and reproduction are linked directly to temperature over the range 0-25°C. The effects of temperature and moisture on, for example, nematode population dynamics in a desert soil have been modelled successfully (Moorhead *et al.*, 1987). The feeding of smaller invertebrates can keep pace with changes in prey density over a range of temperatures. Consequently, it is unlikely that the growth rates of microbial biomass will out-pace the increase in consumption rate by predators. A more probable outcome is a shift in population structure towards species better adapted to the new conditions, but these species will fulfil the same ecological role as their predecessors. Given an increase in temperature of 1-2C°, it is likely that the same processes will occur, albeit with different species participating and at a slightly faster rate.

Changes in soil water content will probably have a much greater impact on faunal activity. Faunal activity has been linked to rainfall events such that there is a burst of microbial and faunal activity and subsequent nutrient cycling. Prolonged changes in soil water content could also have profound effects on soil fauna. Smaller invertebrates are dependent on the air-filled pore space and the thickness of water films in which to move and feed. Larger invertebrates (particularly earthworms) could be active for longer periods if the soil moisture was more favourable during periods that are normally dry. It is likely that changes in soil water content would affect fauna to a greater extent than microorganisms, but more needs to be known about their interactions before accurate predictions can be made.

An important question from an agricultural point of view is whether the role of the soil fauna in nutrient cycling and decomposition will change. In an examination of the role of larger fauna in decomposition processes, it was concluded that changes in temperature were insignificant and that precipitation was the main factor regulating decomposition (Herlitzius, 1987). The effect of rainfall is to enhance primary microbial degradation which increases the palatability of dead plant material to invertebrates. Smaller invertebrates have a greater effect on *net* mineralisation under cool, dry conditions than when it is warm and wet (Persson, 1989). However, it is *gross* mineralisation and *rates* of nutrient turnover that determine the potential availability of N and P to plants. These processes may well be affected differently by invertebrates under different climatic conditions. To realise the implications of global warming on fauna-mediated nutrient cycling requires a better understanding of fauna-micro-organism interactions (in particular, the effects of altered moisture regimes) and their interactions with plants.

II.3 Recommendations for Future Research.

Changes in soil-water regimes and increased [CO_2] have been highlighted as the most important factor affecting the soil physical, chemical and biological processes.

1. Identification of the processes which affect soil structure (physical, biological, chemical) with respect to altered soil-water regime patterns; and the relationship between future wet/dry and freeze/thaw patterns with respect to structural degeneration and regeneration.

2. Determine the effect of changes in plant input patterns as a consequence of elevated [CO_2] on nutrient cycling processes.

3. Study the effects of increased atmospheric [CO_2] on soil N transformations and on the autotrophic fixation of carbon, the consequences of which are not clear.

4. All future research requires an integrated approach in light of the far-reaching changes in climate.

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