1. INTRODUCTION

We are all familiar with the above-ground parts of trees: the trunk, branches, twigs, and leaves: and most people have some understanding of how these grow and develop.

On the other hand, the root systems of trees are something of a mystery to most people; including many who are involved with farming, gardening, building and other occupations where they occasionally come across tree roots.

A popular misconception is that the roots of a tree are a mirror-image of the above-ground parts, with roots extending down into the ground for several metres. Fig.1 shows a diagram which was included in an information package published by the Countryside Commission following the severe gale which crossed south-east England in October 1987. Assuming that this tree is about 20m tall, the roots are shown as extending laterally for about 7.5m and downwards for about 5m. This may be possible under some conditions, but it does not represent a typical tree root system.

A typical root system is shown in Fig. 2, with fine roots extending laterally for a greater distance and with the majority of roots in the upper lm of soil, or less.

Another misconception is that there is a reasonably predictable relationship between the height of a tree and the lateral extent of its roots, or between the spread of its branches and the extent of roots. While there may be some relationship, it is by no means constant for all tree species or site conditions.

A further misconception which is widely held is that most trees obtain a significant amount of water from "the water table" (Helliwell, 1992); and where trees have suffered die-back or death from other causes, this is often wrongly attributed to "a lowering of the water table".

The experience of the authors of this booklet is restricted mainly to the British Isles, and the booklet is written with British readers in mind. But literature from other countries indicates that tree root systems in other countries are not, in general greatly different from those in Britain. Even in tropical climates it is not usual for tree roots to extend to very great depths (e.g. Dabral *et al.*, 1987, Ogigirigi and Igboanugo, 1985) although they can sometimes do so.

Perry (1982), in a very readable and forthright paper, also states that most tree roots are usually found in the upper lm, but quotes instances where roots can grow to depths of 10m or more, on uncompacted, coarse, freely-drained soils, e.g. at the foot of steep rocky slopes. Sometimes trees develop a two-tiered root system, with an upper layer of roots near the soil surface, where conditions are favourable and nutrient supply is greatest, and a lower layer growing just above the soil layers where oxygen supplies are insufficient to support growth. As Perry says, this enables such trees to absorb moisture and nutrients made available by intermittent rains and to survive during drought.

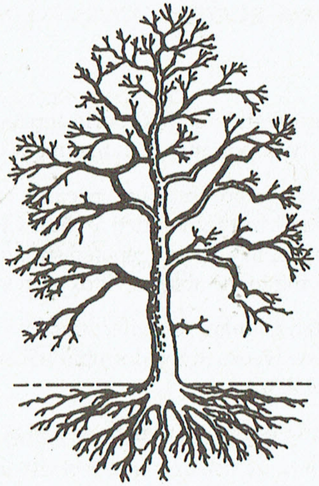

Fig . 1

Popular conception of tree roots

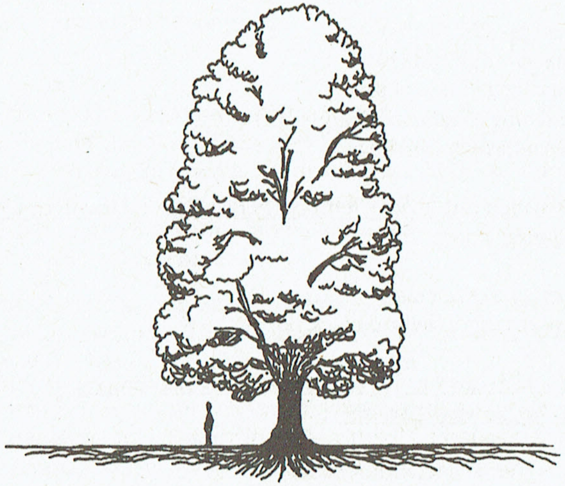

Fig . 2

Realistic representation of tree roots

2. FUNCTIONING OF TREE ROOTS

Air

Most tree roots will not grow if the soil is poorly aerated. Roots need oxygen to survive, and this is particularly important when the tree is growing vigorously.

Some tree species, such as mangroves, have specially adapted roots, with "breathing tubes" to the surface; and some, such as alders and willows, will grow in partly waterlogged conditions or in well oxygenated stream or pond water; but most species are incapable of growing in the absence of oxygen in the soil.

If air is displaced by water, methane, or other substances for more than a few days in the growing season, or a few weeks in the dormant season, the roots in the affected soil are likely to die (Hosner,1958).

If sufficient roots die, then the growth of the tree will be affected and, in severe cases, the whole tree may die.

Different tree species have different degrees of tolerance. Schaffer *et al.* (1992) have studied various fruit crops.

Duchaufour (1960) classifies forest trees into four groups, of increasing tolerance:

i. Species which require well-aerated soil at all times:-

e.g. *Abies* spp. (Silver firs)
Fagus sylvatica (beech)
Pinus nigra (black pines)
Pseudotsuga menziesii (Douglas fir)
Quercus petraea (sessile oak)

ii. Species which can survive temporary flooding if it involves well aerated cold, flowing water:-

e.g. *Fraxinus excelsior* (ash)
Populus x nigra (hybrid black poplars)

iii. Species which can survive a short period of flooding by standing water, outside the growing season:-

e.g. *Alnus glutinosa* (common alder)
Pinus pinaster (maritime pine)
Pinus strobus (Weymouth pine)
Thuya plicata (Western red cedar)

iv. Species which are very resistant to asphyxiation of the roots even during the growing season:-

e.g. *Betula pubescens* (downy birch)
Frangula alnus (alder buckthorn)
Salix spp. (some species of willow).

It must be recognised that these are not precise categories, and the effects of saturation of the soil with water will vary with the quality of the water, temperature, season, atmospheric humidity and windspeed.

The need for tree roots to be supplied with oxygen is often forgotten, but it is one of their most important requirements.

Water

Trees require large amounts of water. This is taken up by the fine roots, and most of it then passes up the tree to the leaves where it evaporates into the atmosphere. This process involves the use of energy by the roots, which in turn requires the presence of oxygen.

Different soils hold different amounts of water, not all of which is "available" to roots, as some of it is held too firmly by the soil particles. Table 1 lists typical "available water capacities" to lm depth of various soil types.

Trees can suffer stress or die from lack of water even when the soil contains plenty of water, if the soil is frozen or waterlogged.

Anchorage

Trees need a firm anchorage to prevent them from being blown over by strong winds. Most mature trees stand on a "root plate" consisting of fairly thick roots more than 30mm thick, which usually extends no further than about one third as far from the stem as the branches. For example, a tree with branches which spread 9m from the stem is likely to have a root plate with a radius of less than 3m, although the finer roots may extend much further than this.

The root plate acts as a base on which the tree rests; and this is anchored into the surrounding soil by thinner roots. These thinner roots are fairly strong under tension but are easily cut by machinery or broken if they are bent.

"Tap roots", which are commonly found in young seedlings of some species such as oak, are a much less common feature in mature trees. Gasson and Cutler (1990) report that, for example, "The majority of oaks have root systems consisting of laterals or laterals and droppers, and a small proportion have tap roots or sloping root systems".

Sometimes the root plate is anchored into the soil or rock beneath it, by "droppers", but not if this soil is very compacted or if it is waterlogged for long periods each year.

Barriers to root growth (such as permanently wet ditches or walls with deep foundations), or the severance of roots (e.g. by the digging of trenches for water pipes) can reduce anchorage and make trees liable to be blown over. Additionally, trees which grow in soils which are frequently waterlogged to within a few cm of the surface (such as many conifer plantations on gley soils or peat) are particularly susceptible to "windthrow" (i.e. being blown over).

Nutrients

Trees require nutrients, just like other plants. Some, such as walnuts and most poplars, require moderately high levels of fertility to grow well, but many tree species will grow well with relatively low levels of nutrients.

Nutrient deficiency is usually the least difficult problem to solve, but can be relatively expensive to rectify in extremely acid or extremely calcareous materials.

3. TREE ROOTS AND WATER

Water requirements of trees

In warm, dry windy weather in southern England a tree in full leaf can take up the equivalent of more than 3mm of rainfall per day from the area of soil occupied by its roots. Figures of more than 7mm per day are recorded from other parts of the world (Whitehead and Jarvis,1981). A typical figure for annual uptake of water by trees in coniferous forests in Europe is around 330mm (Roberts,1983), which is an approximate average of 2mm per day for six months.

A tree of modest size, say 12m tall, with branches spreading 4m and the main concentration of roots spreading 6m from the stem, covering an area of about 110m^2 may therefore be expected to take up more than 40,000 litres of water each year.

As the soil near the surface becomes dry, the tree relies to a greater extent on roots at greater depth (Eastham *et al.* 1990). If the whole volume of soil exploited by the roots becomes dry, the leaves on the tree will wilt and eventually die.

Water requirements will be very small for deciduous trees while they are leafless, and greatest for both deciduous and evergreen trees in hot dry weather.

Trees in sheltered locations or growing within a closed canopy will also require less water than isolated trees in unsheltered locations.

In addition to taking water from the soil, trees can also intercept large amounts of precipitation, which evaporates directly back into the atmosphere without reaching the ground. In south-east England about 15-20% of annual rainfall is likely to be intercepted and 'lost" in this way on land covered by deciduous broadleaved trees and about 30-40% on land covered with evergreen coniferous trees (Aussenac,1970; Ovington, 1954).

Rainfall and moisture deficits

Over much of Britain there are, in every year, periods varying from days to months when the water used by a tree exceeds the amount falling as rain. Under these conditions the tree has to use the moisture which is available in the soil. The water content of the soil is therefore decreased and a "soil moisture deficit" develops.

In south-east England, soil moisture deficits under trees in dry summers may be as much as 200mm or more: that is, over a period of several months during the growing season, the amount of moisture which could be used will be 200mm more than the actual rainfall during that period. In that event, the moisture required by the tree has to be supplied by the soil. If this is not adequate, the tree ceases to grow and may shed its leaves prematurely (if it is deciduous) or die.

Even in parts of Britain with a high average rainfall there can be periods when the rainfall is not sufficient to maintain a high level of available moisture in the soil.

Studies of the growth rings of trees often indicate years when the rainfall was below average. Narrow growth rings are produced in such years, reflecting the fact that under such conditions the tree was not able to grow as much as in years with more rainfall.

Reference to Table 1 shows that in order to make good a deficit of 200mm from moisture reserves in the soil, there would need to be roots to a depth of more than lm in most soils. If the roots are shallower than that, the tree will grow poorly or may even die in a very dry year.

Other vegetation, such as grass, bracken, or shrubs may also be using water from the soil, and may use larger amounts than the trees in newly-planted or fairly open woodland (Whitehead and Jarvis,1981). Control of weeds around newly planted trees is particularly important, in order to reduce the amount of water taken up, and can have a dramatic effect on survival and growth of the young trees (Davies, 1987).

Water tables

As noted on page 1, the role of "the water table" in supplying water to trees is often over-emphasised, and is a recurring source of misunderstanding (Helliwell, 1992).

Fig. 3 illustrates trees growing on limestone in a position where the nearest water table is at least 100m below the soil surface and clearly contributes nothing to the growth of the trees. The trees which are nearest to the edge of the quarry may have lost some of their roots, and they may be more exposed to the wind, causing some decline in growth, but there is no effect related to the water table, as is often suggested in such situations.

Fig. 3

Trees on limestone close to a quarry in Derbyshire, not affected by any 'water table'

More than a century ago it was known (e.g. Wollny,1885) that the height to which water could rise by capillary action in materials such as gravel or coarse sand was very small; a matter of perhaps 200-400mm, depending on the size of the particles. In relatively homogeneous loamy soil profiles it can rise by a metre or more, and by a greater distance in clay soils. However, in fine grained soils, such as clays, the rate of movement is slow, and the amount of water which can be supplied to the rooting zone may not be sufficient to replenish the amounts used by tree roots (Duchaufour, 1960).

The maximum height, under ideal conditions, over which capillary action can be effective depends on the soil materials, and varies accordingly. Wind (1961) quotes a typical maximum as being about lm. However, in some silty soils and on unfractured chalk, useful contributions can be made over greater heights than this. For example, Wellings and Bell (1980) and Wellings (1984) have shown that water can rise from depths of 3 to 6m in some chalks, if there is capillary continuity, but this is unusual.

The rate of rise is dependent on the juxtaposition of various particle sizes in the soil profile.

There is at least one situation where a water table can have a beneficial effect on tree growth. This is on sandy or loamy soils with a permanent water table within rooting depth, or within sufficiently close proximity to roots for capillary rise to be effective. Typically, this will be in the order of 2 to 4m below the soil surface.

Trees growing in such a situation can establish a balance of shoot to root which relies on the supply of water from the water table. If the water table is then suddenly lowered, for example as a result of pumping for irrigation or to facilitate gravel extraction, the trees may suffer. In extreme cases this can cause extensive die-back or even death of trees.

In some circumstances the water table may fall naturally in dry weather and may then be too far down to contribute to water supply in the rooting zone (e.g. Rutter and Fourt,1965).

However, in most soils, tree roots are totally dependent on the water stored within the soil in which the roots are growing, with no appreciable contribution from water at greater depths. In other words, trees (and other vegetation) are dependent on recent rainfall and the storage capacity of the soil.

In a detailed study in the Dutch polders, Visser (1983) found that the best production from fruit trees was obtained when the ground water was at a deep level and effectively out of reach. Under those circumstances "the supply of moisture remains fully sufficient, partly because deep root formation is possible."

The most extensive group of soils in England and Wales is surface-water gleys (Avery *et al.* 1975), which are predominant over about 50% of this area. Such soils are usually fine-textured and more or less severely affected by a seasonal "water table" that is "perched" on poorly-permeable or impermeable subsoil at a depth of less than 0.8m. Such soils are "wet" in winter, and often unseasonably wet in wet years, due to the impermeable subsoil. This wetness is not related to any water table (*sensu stricto)*, and the impermeable subsoil effectively separates tree root systems from any ground water at greater depth.

However, it is sometimes possible for tree roots to grow down into the subsoil in dry weather and to abstract moisture and thereby make it drier. In areas of relatively low rainfall, the soil at depth may not be fully re-wetted during the following winter, particularly if the site is sloping or if some of the soil is covered by roads and buildings with a drainage system which removes water from the site. In such cases, tree roots may be found at greater depths than would be expected.

Nevertheless, the tree is still dependent on the amount of rain which falls on the site; which is not intercepted by vegetation or hard surfaces; and which percolates into the soil. The presence of roots at greater depth may, however, enable the tree to withstand a severe drought better than a tree with roots confined to the upper 1m. These deeper roots may die back if there is a series of years with higher than average rainfall.

4. EXTENT AND DEPTH OF ROOT SYSTEMS

Fig.4 shows the typical depth and spread of tree roots, on a "typical" soil, in Britain. Helliwell (1986) has suggested a formula for calculating the volume of soil required by a tree, related to

climate
soil type (water holding capacity)
soil fertility
exposure to wind,

where there is no water table close to the surface, no significant capillary rise, and excluding the effects of other vegetation.

The volume of soil required by a tree which is 20m tall, branched to ground level and with an average branch spread of 6m (i.e.12m crown diameter) is likely to vary between 50m^3 and 680m^3 in different locations in Britain, with a "typical" situation being about 250m^3.

If a tree in such a typical situation is utilising a soil depth of lm, then the tree will require a rooting area of 250m^2 (i.e. a radius of about 9m). If roots are restricted to the upper 0.5m, it will require at least 500m^2 (a radius of 12.6m)

Where trees are closely spaced they tend to root more deeply, but only by a factor of around 25% (Eastham *et al.* 1990). The individual water requirement of each tree will be less under such conditions, due to reduced exposure to the drying effects of wind.

Goldstein *et al.* (1991) predict very similar soil volume requirements in the U.S.A. A tree 10.7m tall and with a crown diameter of 6.1m (i.e. about one seventh as large as the example quoted above, in terms of crown volume) is predicted to require about 12m^3 of soil in Minneapolis, 21m^3 in Seattle, and 194m^3 in Phoenix, Arizona.

Trees in arid regions usually grow at fairly wide spacing, as the roots require a larger area than the tree canopy, unless they are growing close to a river or other source of water. Nahmias (1989) recommends planting trees at initial spacings of 7 to 9m in a region with only 200mm annual rainfall, rather than the spacings of 2 to 3m which are normal in moister regions.

These latter examples may not seem relevant to British conditions, but they serve to illustrate the principles which are involved, which are the same in all parts of the world.

The depth of tree root systems can vary from as little as a few cm in heavy clay soils or peat in areas of high rainfall, to several metres in freely-drained soils in warm climates (Eastham *et al, 1990).* In the former soils, even a shallow ploughed furrow can act as a barrier to the lateral growth of a root system (Savill,1976).

On the other hand, soil conditions between buildings, roads, and car parks in urban areas can sometimes be very "dry", and in such situations in southern England, roots have been found at depths as great as 5m, in locations where insufficient water reaches the soil for it to be thoroughly moistened each winter; but more typical maximum depths in less confined situations are between 1 and 2m, with some species reaching 3m (e.g. Biddle,1983).

Even in drier climates the majority of tree roots are usually found in the upper lm or less, with relatively few roots penetrating deeper than 2 or 3m. For example, in India, Dabral *et al.* (1987) were able to trace roots of *Eucalyptus camaldulensis* laterally to an average distance of more than 20m, but vertically to less than 3m. Ogigirigi and Igboanugo (1985) report that most native species in the Nigerian savanna failed to penetrate an iron pan at a depth of 40-60cm, although several exotic species were able to, and sent roots to depths exceeding 90cm.

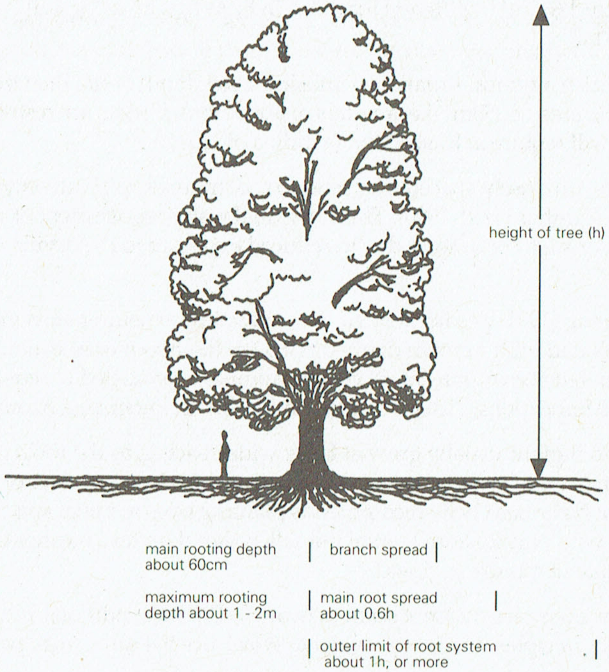

Fig. 4

Dimensions of typical root system

(An indication of root spread of a typical free-standing tree, where root development is unimpeded by ditches, walls, or other obstructions)

5. TREE SPECIES

There is evidence that some tree species use water more efficiently than others when it is in short supply (Ranney *et al., 1990);* although Goldstein *et al.* (1991) report that the amount of water used by four tree species *(Tilia americana, Fraxinus americana, Sophora japonica,* and a cultivar of *Amelanchier)* was very similar, and differed only in relation to the canopy size of the tree.

Published lists showing rank orders of the water requirements of different species are not always in agreement with each other (Biddle,1979), although there seems to be general agreement that poplars use more than other trees. *Pinus contorta* (Lodgepole pine) also has a reputation for removing more moisture from the soil than other species (Pyatt and Craven,1979).

Some tree species tend to root more deeply than others, with poplars and oaks among the more deeply rooted, and birches and beech among the more shallow rooted species.

6. TREE ROOTS AND BUILDINGS

Tree roots can cause problems in urban areas due to:

i) Forces exerted by growing roots.

Roots may lift and crack paving, pipes, and light structures such as garden walls.

The forces exerted as roots grow and become thicker are not sufficient to disturb heavier structures; and roots growing beneath the foundations of a two-storey house will be unable to thicken normally. However, if a tree is growing so close to a wall that the root buttresses touch it, lateral pressure can be exerted and damage caused, if the other side of the wall is not restrained by the presence of soil or some other solid material.

ii) Penetration and blockage of drains.

Roots can only penetrate drains if there are joints or cracks through which they can enter. Modern drains are unlikely to become blocked unless damaged in some way.

iii) Changing the moisture content of clay soils beneath foundations.

Roots can reduce the moisture content of clay and cause it to shrink. Some types of clay shrink more than others: soils with little or no clay do not shrink significantly on drying. Shrinkage of clay beneath foundations can cause subsidence and cracking of walls.

Conversely, if a tree is removed shortly before building a house, clay soil can swell as it regains moisture and cause "heave" which, like subsidence, can result in cracks in a building.

The National House-Building Council (1992) has issued detailed guidance on the type and depth of foundations needed to avoid damage from this cause, and the distances at which it is safe to grow trees of various types. The shrinkability of the soil, depth of foundations and geographical location are all relevant.

7. EFFECTS OF VARIOUS OPERATIONS ON TREE ROOTS

Root severance

It is very common for roots to be cut during the excavation of trenches for water pipes, drains, or other services; and the plant operator or site foreman may say that no roots were cut. However, what he means is that he encountered no very thick roots. Nevertheless, numerous roots less than 10mm diameter may have been cut, and in this way a major part of the root system of a tree can have been severed. If more than about 30-40% of the root system of a mature tree is severed, some effect on the tree is likely to become evident. Younger trees can usually survive greater loss, but fully mature or over-mature trees may suffer some degree of die-back from as little as 10-20% loss of roots.

Changes in soil levels

It is very common on building sites for all topsoil to be stripped and placed in piles, for later use. The topsoil may contain more than 50% of tree roots, and this action can therefore be very harmful.

Any significant reduction in soil level within the rooting area of a tree is likely to be harmful.

Equally, raising the level of the soil can be harmful if the added soil is deep, clayey, or compacted, as it can prevent air from reaching the roots. For example, mature trees are likely to be killed if earth bunds, to screen houses or roads, are placed over more than about 30% of their root systems.

Compaction

If vehicles or other machinery pass over the soil in the rooting area, or if heavy materials are stored, particularly when the soil is wet, the soil can become compacted. This can exclude air and cause the death of roots.

Cultivation

Cultivation of the soil can cause damage to roots, particularly if the soil has not previously been cultivated during the life of the tree.

Drainage

If drains are dug or soil levels are lowered outside the root area, and drainage is thereby improved, trees are unlikely to be harmed, and may benefit. If, on the other hand, drainage is impeded, this is likely to damage roots.

Installation of drainage systems often causes damage by root severance.

8. SUMMARY

Tree roots do not usually extend as far down into the ground as is popularly supposed.

Roots can often extend for relatively large distances laterally, although this can be influenced by the presence of ditches or other barriers to root growth.

Roots require air to survive, and will normally die if the soil is waterlogged for any long period.

Trees require large amounts of water which, in most instances, is obtained from the "available water" held within the soil in which the roots are situated, and only rarely by capillary action from a "water table".

Damage to tree roots can affect the health, stability, and survival of trees, and such damage may arise from a variety of causes.

Tree roots can, in some circumstances, cause damage to property.

9. ACKNOWLEDGEMENTS

We would like to acknowledge helpful comments and suggestions from P.G. Biddle, A.J. Moffat and T.R. Worthington.

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Table 1

Typical amounts of available water capacity for different soil types (in mm per lm depth soil profile)*

Thin soils over more or less fractured hard rock	10	-	115
Thin soils over chalk	125	-	150
Sandy soils over soft sandstone	85	-	145
Thick sandy soils	100	-	145
Thick loamy and silty soils	130	-	195
Loamy and silty over clayey soils	135	-	150
Clayey soils	115	-	170
Thick peat soils	200	-	300
Gravelly soils	50	-	90
Podzols	50	-	120

All these figures will vary, depending upon predominant sand size, stone content, structural conditions and clay mineralogy, where applicable.

Accessible groundwater in summer, if present, would give higher figures.

* Calculations can be made according to individual soil profile characteristics using the data in MAFF (1988) Appendix 4 pp. 46-50.

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Reading Agricultural Consultants

The current Partnership is the successor to a consultancy incorporated in 1964 and in continuous practice since then.

The firm operates throughout Great Britain and covers a wide range of activities including agricultural and ecological impact assessments and technical advice on specific problems in agriculture, land restoration, habitat transference, and vegetation management. Advice is frequently required in connection with planning applications, public inquiries, insurance claims, and litigation; and the firm has been involved in a number of major projects including the Channel Tunnel and various motorway modifications, through to smaller cases such as compensation for SSSI designation, farm diversification, claims for damaged crops, and use of farm buildings.