FORESTRY COMMISSION

BULLETIN No. 18

SPRING FROSTS

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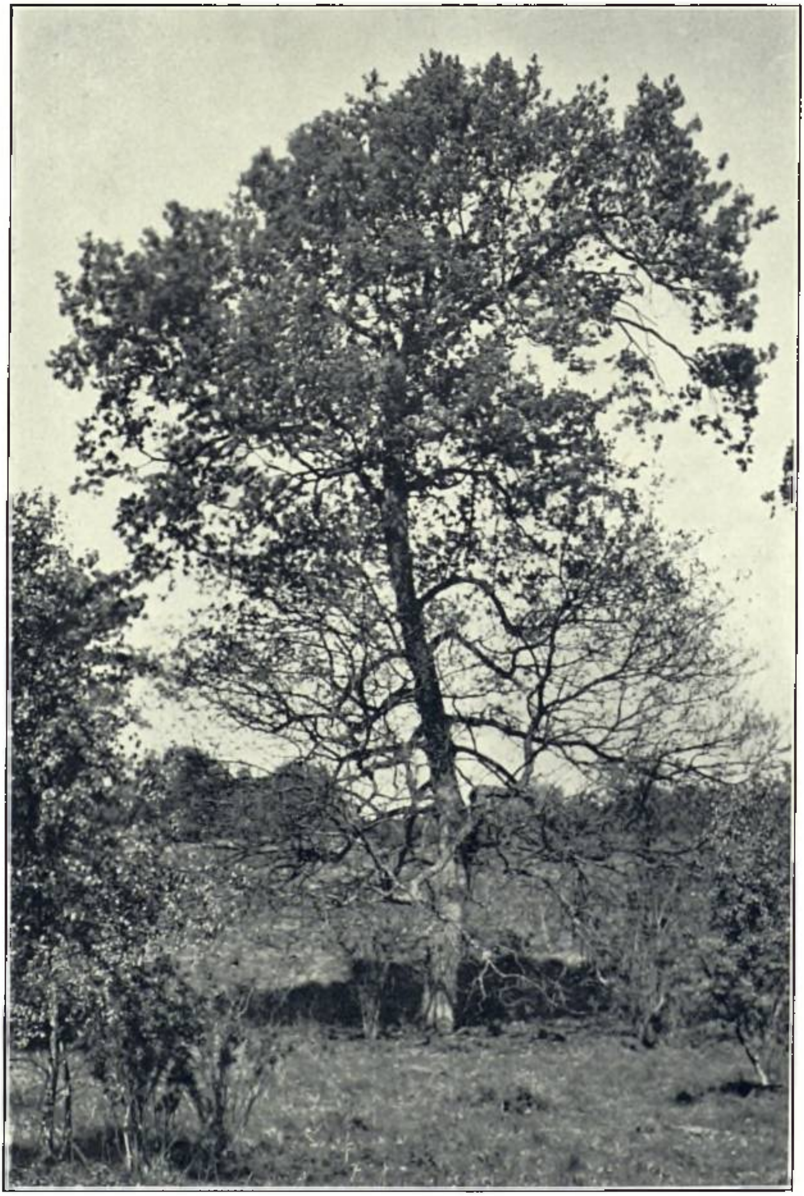

Oak at Santon Downham, Norfolk, frosted to a height of twenty feet. Above the level of the freezing air the shoots were undamaged.

Photo : M. Nimmo, May 1935.

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SPRING FROSTS

WITH SPECIAL REFERENCE TO THE FROSTS OF MAY 1935

LONDON
PUBLISHED BY HIS MAJESTY'S STATIONERY OFFICE
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PREFACE.

THIS Bulletin is the work of Mr. W. R. Day, B.Sc., M.A., and Mr. T. R. Peace, M.A., of the Imperial Forestry Institute, Oxford.

Spring frosts add considerably to the difficulties of establishing young plantations. Investigations which the Imperial Forestry Institute had been carrying out for the Forestry Commission since 1929 were already yielding interesting results when the great May frosts of 1935 occurred. These frosts were so widespread and did so much damage that it was decided to study the whole subject in detail.

In nature most forest trees regenerate themselves in gaps in the old woods or under the shelter of parent trees. In afforesting bare ground absence of shelter renders it important in frosty places to plant only such species as are known to be frost-hardy. There are consequently two problems: to recognise frosty areas in advance of planting and to assess the frost-hardiness of different species of trees. This Bulletin deals with both. Detailed attention is given to the climate of the ground air zone within which trees live and to susceptibility of forest trees to damage by spring frost. The main concern is with trees of economic importance but the lists indicating the relative frost-hardiness of numerous ornamental trees and shrubs will perhaps also be useful to gardeners and others who plant for amenity.

Very little has been written in English on the subject of forest meteorology. It is hoped that this Bulletin will at least direct attention to the importance of the question.

R. L. ROBINSON,
Chairman.

Forestry Commission,
9 Savile Row, London, W.1.
May, 1937.

AUTHORS' ACKNOWLEDGMENTS.

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Mr. F. J. Day's assistance was most valuable in extracting and classifying the data in reports and letters received from correspondents who, in 1935, replied to the authors' enquiry in *The Times* regarding damage done by the May frosts. The authors also desire to express their indebtedness to the officers and foresters of the Forestry Commission for their help and especially to thank Mr. James Macdonald and Mr. M. Nimmo. A small grant received from the Schlich Memorial Fund Committee was a useful contribution towards the accomplishment of the work and is gratefully acknowledged.

BULLETIN No. 18.

SPRING FROSTS.

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SPRING FROSTS.

INTRODUCTION.

MORE alarm was caused by the mid-May frosts of 1935 than by any occurrence of the kind during recent years. Practically everyone connected with the growing of plants was affected. The frosty conditions covered the whole of Britain and caused general injury to plant life, and especially to trees.

These severe frosts drew attention to the fact that not nearly enough is known of the climate within which plants live. It has, of course, long been recognised that there is a close relationship between the health of plants and the climatic conditions prevailing for the time being, but exactly how plants respond to variations and the extent to which variations are directly or indirectly causes of disease are matters still imperfectly understood. Even with regard to such an apparently simple matter as frost there is much to be learned.

The Ground Air Zone.

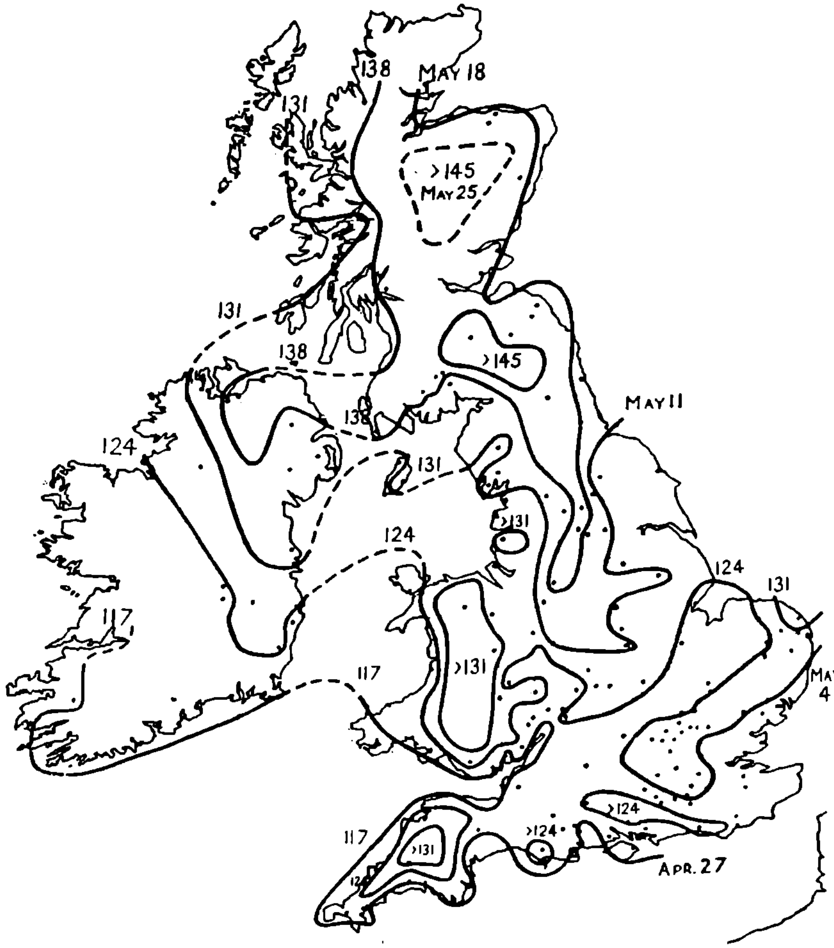
Until recent years meteorologists have paid more attention to general climatic conditions than to the conditions at particular points within the ground air zone, *i.e.*, the air immediately adjacent to that surface. Most forms of life on land live within this zone, and frosts direct us to the study of the climate within it, for it was there that the frost damage occurred. The conditions prevailing at a particular point in the ground air zone are known as the micro-climate, in distinction to the " general " climate which prevails over larger areas.

The ground zone of the atmosphere is usually very thin. It may be defined, meteorologically, as that zone within which the physical conditions of the air are rapidly affected by changes in the physical conditions of the earth's surface; that is to say by heating and cooling, wetting and drying, which go on by day and night under varying weather conditions. The depth of the zone depends on the general weather conditions prevailing, the type of vegetation covering the soil, the physical state of the soil and of the super-adjacent atmosphere, and the topography of the country. The surface vegetation is, in this connection, to be regarded as an extension of the earth's surface and not physically distinct from it. The extent to which this penetrates up into the air or down into the soil gives an indication of the particular parts of the atmosphere and of the earth with the climate of which the cultivator and biologist are specially interested. Thus most herbaceous plants stand within six feet of the soil and in this country trees are rarely more than one hundred feet high. Beneath the soil the root systems of plants are chiefly confined to within six feet of the surface. The physical condition of this part of the earth is of considerable importance in the study of the micro-climate.

The systematic collection of meteorological and biological data in Britain relevant to the study of the micro-climate has hardly begun. In forestry a start has been made in the collection of phenological and meteorological data, and for the past eight years research has been carried out into frost as a cause of disease in forest trees. There is, however, much to be done.

State of Vegetation in May.

In woodland, and especially deciduous woodland, April is the month of bursting buds. The prevailing impression is of bare trees which are just beginning to show green, or at least markedly to change in colour owing to the expansion of the buds. The forest canopy of leaves is as yet unformed, and beneath the trees typical spring flowers such as primroses, anemones, celandines and violets are to be found. In hedgerows the blackthorn is in full flower and, with the exception of the larch, which may be in full leaf on its dwarf shoots in April, the conifers have not burst their buds. In May, on the other hand, the deciduous woodland gives an impression of fresh newly expanded greenery. By the middle of the month most of the common broad-leaved trees have their leaves appreciably expanded, the ash usually being the latest. The early spring flowers of the woodland now die away; the bluebell becomes the dominant flower, the curled bracken fronds appearing at the same time. Of the broadleaved trees, beech, ash, oak and sycamore are in flower. The blackthorn is past its best, and by the middle of the month the hawthorn and apple trees are approaching full bloom. The tree willows are in flower and early leaf during the latter part of April and the beginning of May, also the early leafing poplars, such as the balsam poplar, *Populus candicans*; but the later flushing ones, such as the common black Italian poplar, *Populus serotina*, with its brilliant copper-coloured young leaves, only show an appreciable amount of foliage by the middle of May. The European and Japanese larches, which were already in full leaf on their dwarf shoots, begin to form long shoots during the first half of May. The evergreen conifers have begun to burst their buds at the beginning of the month, but by the middle they are nearly all flushed. There is some variation in the state of development according to variety and species. Thus the later flushing Norway spruce and green Douglas fir may not yet be out, while the latter species, as a whole, may flush somewhat later than the Sitka spruce, as in 1935. In any one genus, as *e.g.*, in *Abies* (silver fir) there is a considerable variation in development according to the species. The Scots pine is in the stage when the new shoots rise up as silvery candles without showing any appreciable length of green needle. Beneath the soil, roots generally have been active since the end of the winter, while on the stems and shoots new wood, which had already begun to be laid down by the end of April, is being formed rapidly. May is thus a month of intense activity in growth and development. In warmer parts of Britain the programme of events may be a little earlier than elsewhere, and in cooler parts, *i.e.*, in the north-eastern part of the island and at the higher elevations, a little later (*see* Map 1, and Ref. 3).



MAP 1.

Map of average floral isophenes, or lines of equal flowering dates, of typical plants for the years 1891–1925. The figures refer to the number of days from 1st January.

From the Phenological Report, 1935, *of the Royal Meteorological Society.*

The date at which a plant comes into leaf or flower is also affected by the season. There is commonly a difference of as much as a fortnight and sometimes of more than a month in time of flowering between early and late seasons as is shown, for example, by Church [8]. It is evident therefore that, as a plant is less sensitive to frost before its new shoots have appeared than after, the amount of damage done when severe spring frosts occur depends not only on the date of the freezing but also on the state of the new season's growth. In 1935, owing to a mild winter and a heat wave in early May [3], vegetation came into growth earlier than usual and this influenced the severity of the damage done by the spring frosts.

Frequency of May Frosts in recent Years.

There are practically no records from forest areas on which to base a judgment with regard to the frequency with which damaging frosts occur in May and the only information available is that given by the daily[1] and monthly [2] meteorological reports issued by the Air Ministry. It has not been possible to work through the daily reports, but an attempt has been made to summarise the information contained in the monthly reports for the ten years 1926–1935. This information is incomplete in that the only relevant data given for each station are the total number of ground frosts, the mean minimum and the absolute monthly minimum screen temperatures. Nevertheless, when a really severe frost occurs affecting a great part of this island most stations tend to have their lowest temperature within the period covered by it. Table I shows the number of stations in each district of Great Britain with absolute minima at or below 28° F., and the total number of stations with absolute minima of 29°, 30° and 31° F. The dates on which the absolute minima chiefly occurred are also given.

The temperature of 28° F. was taken as being a limit below which it might safely be said that a frost had occurred of sufficient severity to cause damage to our common forest trees, in so far as these are usually susceptible. On the other hand, many of the meteorological stations are not in particularly frosty places and damage may have occurred in their vicinity when the minimum screen temperature was above 28°. However this table does not pretend to give a quantitive analysis of May frosts, it is only intended to give an indication of what commonly happens in Britain as regards the occurrence of frost in May. The meteorological districts given in the table are not quite the same as those used by the Air Ministry. Thus in Scotland, the greater part of the north has been missed out and the rest, the southerly portion, added to east and west Scotland. The number of stations in each of the districts, in 1935, was as follows :—

Scotland E. (including part of Scotland N.) ..	39
Scotland W. (including part of Scotland N.) ..	27
England N.E.	18
England N.W. and Wales N.	27
England E.	25
England Midlands	43
England S.E.	52
England S.W. and Wales S.	37

TABLE I.

Number of Meteorological Stations with the Absolute Minimum Screen Temperature for May at or below 31° F., together with the Dates of Occurrence.

District.	1935.	1934.	1933.	1932.	1931.	1930.	1929.	1928.	1927.	1926.
	Number of Stations with Absolute Minima at or below 28° F.									
Scotland E.	16	3	7	10	6	3	13	6	15	5
Scotland W.	9	—	—	7	3	4	7	4	13	9
England N.E.	4	—	—	5	4	5	11	4	10	5
England N.W. & Wales N.	7	—	—	2	1	3	1	—	6	4
England E.	15	1	—	2	3	—	10	3	14	—
England Midlands.	18	1	—	6	3	2	6	4	8	4
England S.E.	19	—	—	1	—	—	8	3	9	—
England S.W. & Wales S.	3	1	—	4	—	—	1	2	—	1
Total at 28° F. or below.	91	6	7	37	20	17	57	26	75	28
Total stations with absolute minima 29, 30 or 31° F.	94	28	17	96	50	52	78	69	72	88
Chief dates (in May).	13,15, 17, 19	3, 17	2	6–10	3, 4, 21	1, 8, 10	1, 2	9–11	1	7–9, 15,16, 19

It may safely be concluded from this table that, during the ten years ending 1935, May frost of sufficient severity to cause injury to our forest trees occurred in every year. Three out of four such frosts occurred in the first half of the month, judging from the limited information available. The table also shows that, during the decade, damaging frosts occurred over wide areas of Britain in every year except 1933 and 1934, and were particularly widespread in 1927, 1929 and 1935. It is evident therefore that damaging May frosts are common and indeed an annual phenomenon in Britain; the only thing exceptional about those of 1935 was their widespread severity. It may be wondered whether frosts occurring on the first of May, as in 1927 and 1929, were capable of causing severe damage, being so much earlier than the mid-May frosts 1935. It so happened that both these frosts caused a great amount of damage; indeed it was the severity of the former which drew our attention to the need of research into frost as a cause of disease in trees. Each year since then we have had, from some part of the country, trees which have been injured by a May frost.

In order to give some idea of the frequency of May frosts over a long period, details are given in the next table of the dates on which, for the forty-four years from 1892–1935, the grass minimum temperature at Radcliffe Observatory, Oxford, was at or below 30°F.* The date on which the lowest temperature occurred is printed in italics and that temperature is also given. The grass minimum temperature at this station has been found to be much the same as that which occurs in May, in Bagley Wood near Oxford, under the shelter of a mixed plantation of larch and ash. The temperatures in Bagley Wood were taken with unscreened grass minimum thermometers and there is no reason to think that they are exceptional for similar situations in the Oxford district.

TABLE II.

Year.	Days in May on which Grass Minimum Temperature was at or below 30° F. at the Radcliffe Observatory, Oxford.	Lowest Temperature.
1892	1, 2, 6, *7*, 9 ..	20·4
1893	7, *11*	28·4
1894	*21*, 22	26·3
1895	*2*	29·9
1896	*1*, 2, 4, 5 ..	23·8
1897	11, 12, *13* ..	25·4
1898	13, *17*	29·3
1899	4, *5*, 26, 27, 28 ..	26·5
1900	11, *16*	28·2
1901	*5*, 18	26·6
1902	5, 7, *10*, 13, 14 ..	26·4
1903		
1904	3, 4, 8, 9, 11, *20*	26·4
1905	4, 6, 9, 22, *23*, 24	23·4
1906	1, *2*, 5, 18, 19 ..	21·4
1907	*19*	27·7
1908		

* It is important to note that the grass minimum thermometer usually gives a substantially lower reading than the screened minimum thermometer. The data in Table II are therefore not directly comparable with the data in Table I.

TABLE II.—*continued.*

Year.	Days in May on which Grass Minimum Temperature was at or below 30° F. at the Radcliffe Observatory, Oxford.	Lowest Temperature.
1909	1, 2, 3, 4, 9, 11, 13, *15*, 18, 19, 20	24·9
1910	3 8, 9, 10, *11*	23·9
1911		
1912	*1*	24·7
1913	*7*	28·6
1914	*2*, 26, 27	22·3
1915	10, *15*, 19, 31	26·0
1916		
1917	*7*, 9	24·4
1918		
1919		
1920		
1921	*5*	25·5
1922	*13*, 14	24·4
1923	*12*, 24, 26	27·6
1924	*5*	28·7
1925	1, *2*	29·2
1926	*9*, 16	27·7
1927	*1*, 2, 12, 28, 29	21·9
1928	8, 9, *10*, 15, 19, 20	22·9
1929	1, *2*, 3, 20	22·7
1930	*1*	28·8
1931	*21*	27·9
1932	*6*, 7, 8, 9, 26	28·1
1933	*15*	29·9
1934	*17*	26·2
1935	13, 17, *18*, 19, 21	21·4

An examination of the table shows that in ten of the 44 years, frosts occurred after May 20th, and that in twenty-six, there were frosts after May 15th. The temperature failed to fall to 30° F. in only seven years and five of these occurred in the decade from 1911 to 1920, a period in which, so far as Oxford is concerned, May frosts were comparatively rare. The lowest temperature lay between May 1–10 in twenty years; between May 11–20 in fourteen years; and between May 21–31 in three years. The lowest temperature was at or below 26° in seventeen years and below 23° in seven years, of which four fell in the period 1924–35. There are probably many forest areas in Britain in parts of which the air temperature within the first few feet of the ground falls as low as the lowest temperatures in the above table. The worst of these, indeed, are often made obvious by the marked degree of frost damage which occurs in them.

Considered together, the above tables show that May frosts are commonplace in Britain, that they are mainly confined to the first two-thirds of the month and that an appreciable number of them is markedly severe.

There are, in fact, places which are specially subject to frosts of sufficient severity to injure all but the hardiest plants. The characteristics of such localities are dealt with elsewhere (*see* page 114). In such places as these, frosts are liable to occur at any time of the year, although in the middle of summer they may not be sufficiently severe to cause injury.

General Considerations.

Two points arise from the above. First of all it is plain that unless trees are always hardy it is an advantage if they come into leaf and flower after the period of spring frost is over. Our native trees do, in fact, tend to fall into two categories, those not usually injured by frost, even though they leaf and flower early, and those which are usually injured if severe frost comes after their buds have burst. In the first category fall such trees as sallow, common alder, elms, birch and Scots pine ; in the second one fall oak, beech and ash. Other species hold an intermediate position, for example, white willows may have their flowers killed by May frosts when the leaves are unhurt. Naturally much depends on the severity of the frost.

The second point arising is that the micro-climate varies from place to place, one locality being more favourable than another perhaps adjacent to it. This has long been recognised. Therefore the wise fruit grower will choose the least frosty site for the establishing of his orchards; the forester knows that frost causes trouble in hollows and on level ground.

In practical forestry and arboriculture it is therefore important, first that trees shall be grown which are suited to our climate, and still further that they shall be suited to the climate of the locality in which the planting is to take place. Much work has yet to be done before the various species of trees available to us can be used in this way to the greatest advantage. We have to know the various races of trees which may be specially adapted to certain types of micro-climate, and to be sure that any seed used in propagation is really of the strain that we wish to grow. We need also to know a great deal more about the micro-climate to be able to say what climatic extremes may be expected, during the growing season, in any particular locality. The study of frost with its effect upon vegetation in relation to topography, soil conditions and local climate, is one of the most important aspects of this work.

Our attention in this Bulletin has been confined entirely to England, Scotland and Wales. All temperatures are given in degrees Fahrenheit and they are usually minimum temperatures taken either in a screen or in the open over grass with

Meteorological Office pattern thermometers. The screened minimum thermometer is placed in a ventilated box or screen (Stevenson Screen), the bottom of which is 3 ft. 6 in. above a short turf, and is so protected that its bulb is not exposed to loss of heat by radiation to the sky. It may, thus, be taken as indicating the temperature of the air at the level at which it is situated. The grass minimum thermometer, not being so protected is exposed to such loss of heat, and for this reason, and because it is placed above the tips of grass blades where much loss of heat by radiation takes place on clear nights, it registers, especially on such nights, a lower temperature than the screen thermometer. It is probable that the grass minimum is a more accurate indication of the temperature of the plant at the time of freezing. The dew-points quoted are in all cases based on the wet and dry bulb thermometer readings taken at 6 p.m. on the evening preceding the night in question.

TEMPERATURE OF THE GROUND AIR ZONE AND FACTORS AFFECTING IT.

The general weather conditions make the occurrence of severely damaging frosts possible but the actual development of the frosts in the autumn and spring usually depends on special local conditions. A discussion such as this would therefore be incomplete without some reference to the local climatic conditions which so markedly affect the severity of spring frosts, and to the factors which cause them to arise.

The temperature of the ground air zone depends chiefly on the temperature of the surface of the earth. The sun's rays do not warm the atmosphere appreciably in passing through it. They are in part reflected, but in part absorbed by the earth's surface and that portion which is absorbed is changed into heat, which is partly conducted into the earth, warming up a thin outer crust, partly carried by conduction to the adjacent air and partly given off as radiation. During the day the highest air temperatures are, generally speaking, near to the ground, the tendency being for the temperature to fall steadily with elevation. This warmed zone of the atmosphere is comparatively thin.

Advective and Radiation Frosts.

The intermittent warm and cold periods that characterise the British spring have their origin in the air currents which pass over the country. Should the currents come from northerly and cold regions where winter still exists frost is liable to occur; should they come from southerly and warmer regions the weather will be mild. This is not quite the same as saying that northerly winds are cold and southerly winds are warm; generally speaking this is so but locally it may not be true, as is noted in Appendix I (page 110) when discussing the weather during May 1935.

Frosts which arise owing to cold air brought from other regions are known as " advective ". The May frosts in 1935 supply examples of this; on some nights during the frosty period the temperature of the wind was below freezing point. Frosts arising in this way may cause widespread damage, but usually their importance is rather that they make lower and more damaging temperatures possible. Such temperatures occur almost entirely on nights when the sky is clear and the wind very light. The surface of the earth, which here means not merely the soil but also its vegetative or other covering, then loses heat rapidly by radiation which escapes to the outer air, and is thus lost to the ground air zone. The temperature of the cooling surface eventually falls below that of the adjacent air which is further cooled down. If the air is already cold, as on nights when an advective frost is prevailing, very low temperatures can occur, especially in certain localities. Frosts which arise in this manner, are called "radiation" frosts and most of the damaging spring frosts are of this type. Thus the lower temperatures during the mid-May frosts of 1935 occurred as a result of radiation frosts, but they were made possible by the presence of air which was already cold.

Factors affecting the Occurrence of Radiation Frosts.

The degree to which cooling takes place owing to loss of heat by radiation is affected by a number of factors.

Wind.—Radiation takes place on windy nights as much as on calm nights, but the cooled layer of air which forms near the surface of the earth is mixed with the higher and warmer air when the wind is sufficiently strong, and the temperature of the ground air zone is thus prevented from falling as low as it would under calmer conditions.

Cloud and Fog.—The radiation, which on clear nights is lost to the lower air, is partly reflected back and partly absorbed by the water particles in clouds. The cloudier the sky, therefore, the more is heat conserved at night, in the lower air, and the ground air zone prevented from cooling unduly. Fog and mist act in a similar way, but are often too thin and unstable to be very effective. Because clouds have this insulating effect radiation frosts are not to be feared when the sky is overcast. Advective frosts are, however, quite uninfluenced by this and depend merely on the temperature of the wind.

Humidity of the Air.—Any water vapour in the ground air zone is also able to absorb radiation from and thus retain heat near the earth. Also the drier the air the lower must it be cooled before dew, or hoar-frost, is formed. This is important in that, on the condensing of moisture in these forms, heat is liberated which in part compensates for the loss of heat owing to radiation. On calm nights, therefore, destructive frosts are more likely to occur when the air is dry, *i.e.*, when the dew-point is much below the air temperature or the wet bulb temperature below the dry ([28]).

Elevation.—Loss of heat by radiation increases with elevation because the atmosphere becomes clearer and less dense with increasing altitude. On the other hand during the daytime elevated places receive the strongest insolation. These effects are noticed most easily when comparing adjacent places with widely differing altitudes.

Temperature of the radiating Surface.—This is most important and is affected by a number of things.

(i) *Weather.*—A long spell of cold and, during the day, cloudy weather helps to make severe frost possible merely because there is no opportunity for the soil to warm up; the result of this is that each succeeding night, radiation takes place from a colder surface than before. Thus in the mid-May frosts under discussion the weather was, as a whole, cold and dull and the lowest temperature in most places occurred towards the end of the frosty period. Warm, sunny days counteract this tendency even if the temperature drops considerably at night.

(ii) *Type of Surface.*—This is extremely important. The amount of the sun's rays absorbed by the earth's surface depends largely on its physical constitution. Dark-coloured surfaces such as are presented, for example, by peaty soils, readily absorb the sun's radiation, but light-coloured and shiny surfaces largely reflect it. On the other hand for outgoing radiation, *i.e.*, loss of heat during the night, they probably behave much alike.

A great deal depends, also, on whether evaporation is taking place from the surface, for when this occurs much heat is lost. Thus during the day the air is cooler over water, wet soil, or vegetation which is always losing water by transpiration, than over dry rock or soil. At the same time this results in the surface in question being heated up less, and so in its having less heat to give off at night. It will be seen below that this has to be qualified, but nevertheless it remains true that, largely because of loss of heat by evaporation, wet soil surfaces tend also to be cold, frosty ones. In Eastern U.S.A. cranberry marshes are sometimes covered with sand to a depth of about two inches, in order to reduce frost damage; the efficacy of this appears largely to be due to the dry and easily warmed surface which the sand presents as compared with the wet, water-retentive peat(10).

(iii) *Specific Heat of the surface Crust.*—Specific heat is the amount of heat required to raise the temperature of a substance through a given range. This varies with the substance. Water has a high specific heat, while that of most soils when dry is comparatively low. Accordingly water, on being cooled through any particular range of temperature, gives up more heat than do such soil substances. This is the reason for the ameliorating effect of water on frost, especially if present in a large mass, as with the sea or large lakes. Also for this reason there is less likelihood of frost over a wet than over a dry soil providing both begin to cool at much the same temperature. On the other hand during the daytime the loss of heat by evaporation is so much greater from the wet soil that it will start the night too cold for its greater specific heat to give it any advantage. Thus in the case of the cranberry marshes already referred to, the air temperature over undrained peat was from 2 to 8°F. lower than that over drained. In the case of the water-sodden peats so common in the mountainous districts of Britain, draining should also be advantageous in this way; this provides an additional reason for effectively carrying it out when afforestation takes place.

(iv) *Conductivity of the surface Crust.*—The surface crust varies considerably in its capacity for conducting heat. Thus a wet soil has a higher thermal conductivity than a dry one, and a compact soil than a loose one ([17]). The temperature of the radiating surface is affected considerably by the conductivity of the soil beneath. Thus a thick turf acts as an insulating layer, preventing the warming of the soil during the day and the conduction of heat from it to the radiating surface at night. The removal of such turf and the baring of the soil is a decided advantage, so far as the prevention of frost damage is concerned, as under the improved conditions which then exist the soil heats up more during the daytime and the more rapid conduction of heat from below helps to keep the surface of the ground, and so the air immediately above it, warmer at night. The formation of a loose, dry tilth on bare soil also helps to increase the severity of radiation frosts as the surface layer of loose earth which then exists is a bad conductor of heat.

Temperatures in the Ground Air Zone during Radiation Frosts.

The lowest temperatures during a radiation frost are to be found immediately over the radiating surface. If this is bare, level ground, then the lowest temperature occurs immediately over the soil; if, however, it is very irregular, as for example, where the ground is covered with coarse grasses, the lowest temperature may be situated somewhat above the actual soil level because the matted vegetation on the ground covers the soil sufficiently to prevent any appreciable radiation from it. This is illustrated by temperatures quoted by Staudacher ([44]) taken in thick, coarse, tufted grass on 9–10th August, 1922, in the Selenwald.

In grass close to soil - - -	39° F.
At 40 cm. among grass tips - -	36° F.
1 metre above grass tips - - -	40° F.
2 metres above grass tips - - -	43° F.

A similar variation in temperature occurs over short grass. An example of this, taken from Newnham ([29]) is given below. The temperatures were recorded on 3rd February, 1929, on a calm clear night on the lawn of a garden in Hampstead. The height of the grass blades was about one inch and at this height the lowest thermometer was fixed.

TABLE III.

Height above Soil.	Temperature.	
	At 19.00 hrs.	At 22.25 hrs.
Inches.	Degrees F.	
1	26·2	24·1
3	28·2	27·5
5	28·6	27·8
7	28·7	28·3
9	28·7	28·8
11	28·8	28·8

It will be seen that during the time between the two readings the temperature fell most rapidly at the one inch level, *i.e.*, just above the cooling surface. At eleven inches above soil level no fall in temperature had taken place. The influence of the cooling surface upwards is thus comparatively limited. This is also shown by the temperatures given in Table XLI (page 100). It will be seen that the difference between the thermometers in the open and under shelter is much less at a height of three feet than at two inches.

The state of affairs which exists under these conditions is the reverse of that which is usually found during the daytime when most commonly the warmest air is near the ground, the temperature decreasing steadily with increasing elevation. At night during a radiation frost, however, the temperature increases up to a certain point, as one rises from the ground level, and only then decreases with elevation (Fig. I, Ref. 48). This is referred to as an " inversion of temperature ", and when this exists the air in the ground zone is

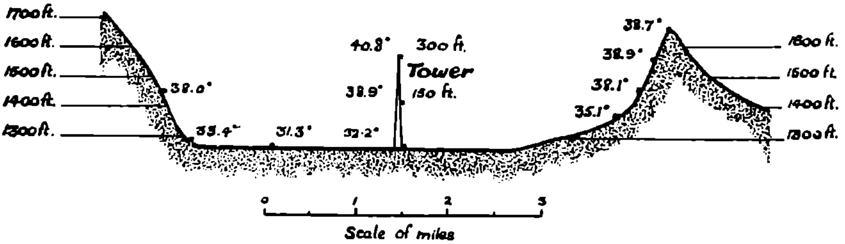


FIG. I.—Temperature conditions in a valley near Medford, Oregon. Mean minimum temperatures for 32 nights in April and May 1918. (*After Young* [48].)

always very still, even though there may be appreciable movement above the inversion level; that is the point beyond which temperatures decrease on ascending. The reason for this stillness is to be found in the lack of opportunity for convection currents to arise. These can only form when the air near the ground is warmer than that above. During a radiation frost, however, the coldest air being always nearest the ground, and being heaviest, no movement can take place.

An example of the differences in temperature with height during the mid-May frosts 1935, is given in Table IV. The temperatures were taken in a frost hollow in Horselawn Inclosure, Forest of Dean, in a recently established spruce plantation where the vegetation consisted of coarse rough grass, largely tussock grass (*Aira caespitosa*), with a little bracken and a little heather (*Calluna vulgaris*).

TABLE IV.

Date (May 1935).	Temperature above Ground Level.		Difference in Temperature.
	At 6 in.	At 2 ft. 6 in.	
	Degrees F.		
14	22·0	22·0	0·0
16	12·0	15·0	3·0
18	10·0	13·0	3·0
20	15·7	20·5	4·8
22	27·5	30·8	3·3
24	29·8	30·9	1·1

The readings were taken every other day on unscreened, grass minimum thermometers and the temperatures for any particular date may have occurred on that day or the day before. The differences in temperature varied according to the clearness of the sky and air and were greatest on clear nights, when conditions were good for free radiation to the sky. It will be noted that the difference in temperature does not vary in accordance with the degree of frost; it is governed by the conditions for radiation.

Further examples of the variation in temperature with height are given in Table V. These figures are taken from the meteorological

TABLE V.

	Bedgebury.				Nagshead.			
Date (May).	Over Grass.	At 1 ft.	At 5 ft.	Diff. Gr.-5 ft.	Over Grass.	At 1 ft.	At 5 ft.	Diff. Gr.-5 ft.
		Degrees F.				Degrees F.		
12	40·0	43·4	44·5	4·5	35·0	40·5	40·5	5·5
13	26·0	28·9	31·1	5·1	20·0	28·0	29·0	9·0
14	26·0	29·0	31·3	5·3	18·0	26·0	27·9	9·9
15	31·0	33·0	34·5	3·5	28·0	34·0	35·0	7·0
16	28·0	29·0	32·0	4·0	34·0	35·0	35·0	1·0
17	19·0	21·0	23·8	4·8	9·0	18·0	20·8	11·8
18	26·0	29·0	31·5	5·5	26·0	30·1	30·8	4·8
19	23·0	26·0	28·1	5·1	15·0	23·8	25·0	10·0
20	40·0	41·0	42·0	2·0	28·0	36·0	37·0	9·0
21	31·0	32·5	34·9	3·9	34·0	37·0	35·0	1·0

stations in the arboretum, Bedgebury, Kent, and in the phenological plots, Nagshead, Forest of Dean.

It will be seen that at both stations during this period there was a marked temperature gradient from the ground upwards, indicating that at least during part of each night conditions were suitable for a radiation frost. The differences in temperature between the various thermometers at Bedgebury agree with those at similar meteorological stations at Lynford, near Thetford, Norfolk, and at Benmore, Argyll. The much higher differences in temperature at Nagshead occur chiefly between the thermometer over the grass and that at one foot. The differences between the latter thermometer and that at five feet are much the same as those which occurred between the similarly placed thermometers at the other stations. The much greater differences at Nagshead between the two lower thermometers are largely to be explained by the temperatures being taken over the tips of long coarse grass whereas at the other stations the grass was short. The two sets of temperatures should not be compared too closely as they were taken at widely separated places, which differ somewhat in climate, elevation and general situation.

In conclusion one may quote the average differences for temperature within the first two metres of the ground air zone given by Hellman ([22]). These were taken over short grass at the Potsdam meteorological station. It is probable that a rather more intense radiation takes place there on clear nights than in the more maritime and humid climate of this country, but the differences are of much the same order.

	Diff. in Temp. Degrees F.
Earth's surface (0·04 in.) to 2·0 in. ..	1·9
2·0 in. to 1 ft. 8 in. above	4·9
1 ft. 8 in. to 6 ft. 8 in. above	3·1
Total difference	9·9

It will be seen that the temperature gradient is very sharp at first; that is, the biggest changes of temperature with height take place near the soil, and this is the general rule during radiation frosts.

Drainage of Cold Air causing Differences in Temperature.

Where the ground is flat, the coldest and, therefore, the heaviest air during a radiation frost lies as a blanket evenly over the soil. Where the ground becomes undulating, however, the colder air on the higher parts drains down into those that are lower. For this reason, on clear nights, the higher parts are often much warmer than the lower, a fact which is, of course, well known.

Some figures illustrating this are given in Table VI below. " X " represents a point on the grass on the north side of the road in front of the Speech House Hotel, Forest of Dean, and at the top of the hill; " Y " a point a furlong and a half to the south-east and down hill, and " Z " about the same distance farther on inside the frost hollow in Horselawn Inclosure shown on Map 5 (page 117), on which the three points are marked.

TABLE VI.

Time (p.m.).	Date.	Temperatures at			Weather.
		Point X.	Point Y.	Point Z.	
			Degrees	F.	
10.00	10.3.31	20·1	—	12·8	Clear sky but inclined to be breezy.
10.15	11.3.31	27·1	22·0	15·0	Clear sky clouding over at time of reading.
10.15	12.3.31	27·0	23·8	16·8	Quite clear, all thermometers falling. Temperature of Z fell to 10·1° F. by morning.
10.00	2.3.32	26·4	24·0	22·0	Clear sky, distance misty, slight breeze.

The marked differences in temperature here recorded are by no means exceptional and may occur at any time of the year when conditions are favourable. It will be seen, as is to be expected from the discussion under radiation, that the smaller differences occurred on evenings when there was a breeze and the least when there was, in addition, sufficient haze to make the distance misty.

TABLE VII.

Date.	Degrees of Temperature at		
	Point D.	Point F.	Point E.
		Degrees F.	
9.7.35	37	—	25
18.7.35	38	31	27
31.7.35	30	—	19
1.8.35	34	29	25
2.8.35	28	22	17

A further illustration of the differences in temperature between hill and valley, taken from an entirely different type of country, is shown in Table VII. The points here are those marked on Map 3 (page 115) : Point D is Lynford meteorological station, 90 ft. elevation and high for the district; Point F is in Compt. 31, Lynford Forest, 500 yds. from the meteorological station and at an elevation of 70 ft.; while E is south-west of Snake Wood (Compt. 132) near Downham, at an elevation of 48 ft. above sea-level and one mile from Lynford. Points E and F are in the same valley while Point D is on the slope above F.

These figures show that even at low elevations it is possible, in suitable areas, to get midsummer (July) frosts of marked severity. Such midsummer frosts also occur in Horselawn, which is, however, at a much higher elevation (550 ft.) on top of the central plateau of the Forest of Dean. If temperatures are taken in several places over a long period it will be seen that any particular locality has its own character. Thus during radiation frosts Point D above will always be warmer than the other two points, weather conditions being similar at each point. Even when there is only a slight hollow the difference in temperature may be considerable. An example is given in Table VIII below, by temperatures taken in Elvedon Forest, Norfolk, Compt. 95. The depth of the hollow is 2 ft. 9 in. and one thermometer was placed at the lower point, the other being set on top of the rise. There was a distance of 140 feet between them and they were set one foot above the ground.

TABLE VIII.

Date.	Degrees of Temperature.		
	Rise.	Hollow.	Difference.
		Degrees F.	
25.4.35	34	33	1·0
26.4.35	37	34	3·0
27.4.35	41	41	0·0
28.4.35	39	39	0·0
29.4.35	42	42	0·0
30.4.35	30	26	4·0
1.5.35	29	27	2·0
2.5.35	20	15	5·0
3.5.35	40	38	2·0
4.5.35	37	36	1·0

The differences are sufficient indication that frost damage might occur in the hollow at times when there was none on the rise.

Those interested in this subject may refer to a paper by Schmidt([42]) on temperatures taken in the Austrian Alps where, in a specially unfavourable situation, a flora containing arctic species was found at the bottom of a frost hollow, on the upper sides of which spruce was growing. The difference in type of flora was definitely correlated to differences in night temperature. While no such extreme case may exist in this country, there are many situations which are similar and in which only the most hardy trees escape injury.

VALLEY WINDS.

The draining of air into hollows and valleys is most marked on perfectly still nights when a movement of air from points of higher to lower elevation may frequently be detected. This movement goes on until the hollows are all filled up with cold air, should this be possible; otherwise it may continue throughout the night, ceasing with the dawn when the surface of the earth begins to warm up again. During the day the reverse takes place; the air nearest the surface of the earth is warmest and, therefore, lighter than that above and tends to rise. When the slope from hill to hollow is sufficiently great this results in marked breezes arising which blow up the valley during the day and downward at night. The night wind begins as soon as the air at any particular point on the slope becomes colder, on the setting of the sun, than the air at the same level but farther away from the earth's surface. The cooler and, therefore, the heavier air flows down the slope and then along the valley bottom in a stratum of increasing thickness. If the valley is long and narrow, and especially if it debouches into another narrow valley, as for example in the rather intricate series of valleys in the moors behind Thornton-le-dale in Yorkshire, the cold air may pile up to a considerable height, much more, in fact, than the height of a tall tree standing in the valley bottom. When this has happened, the air current within the valley may become inappreciable. These downward flowing night breezes are known as "katabatic winds". Their strength depends on the volume of air flowing down from the higher to lower ground, and on the rapidity with which the valley is able to empty itself of this cooler and heavier stratum of air. Katabatic winds are most noticeable on clear still nights, but even if there is a light breeze blowing above the ground air zone they may be strong enough to flow against it. The literature on these winds is scanty, in so far as this country is concerned, the best description of their origin and development in hill country such as occurs in the Cotswold or Chiltern Hills being found in Heywood's "Katabatic Winds in a Valley "[23].

TEMPERATURES IN VALLEYS.

It has been seen above that even in a slight hollow filled with cold air the temperatures are lower than on the adjacent higher ground. In the same way, when a valley is filled with cold air by a katabatic wind, the hilltop is warmer than the valley bottom (Fig. I, page 18). The temperature in the valley, in this case, although influenced by the cooling of the radiating surface of the ground, is not principally determined by it. This is shown very nicely by temperatures taken by J. B. Cohen[9] over Lake Coniston, in September 1900.

Temperatures taken on Lake Coniston on the night of 12th September, 1900 :—

Temp. of Air.	*Temp. of Water.* (Degrees F.)	*Difference.*
48·2	60·8	12·6
46·4	60·8	14·4

In this case the temperature of the air is decidedly lower than that of the water. There can be no doubt that similar conditions occur over land and the fogs which so commonly arise in autumn over water and low fields may, in part, be accounted for by the condensation, by the cold air from the high ground, of the water vapour given off by the comparatively warm water, or soil, as the case may be. Over flat meadows the fogs may be produced merely by the cooling of the air above the meadows owing to radiation. When the temperature of the ground is warm enough, that of the air immediately over it may be sufficiently raised to prevent frost damage to small trees. Osmaston[31] gives this as the reason for the escape of sal regeneration from frost in the United Provinces, India.

Equally interesting in this connection are the temperatures of the air taken at the lake level and up Coniston Old Man.

	Sept. 15.	*Sept.* 16.
	Degrees F.	
At lake level, 150 ft.	47·3	46·4
On slope of Coniston Old Man 1,750 ft. ..	51·8	49·6
On summit of ,, ,, ,, 2,650 ft. ..	52·7	50·9

The temperatures were taken in the morning before sunrise and in order ascending the mountain on the first day and descending the mountain on the second. Fog filled the valley almost to the mountain tops. A similar result is given by temperatures taken at about the same time on the top of Ben Nevis and at Fort William[9]. Thus at 6.0 a.m. on 12th September, 1900, the temperature on the top of the mountain was 53·5°, while that in the valley was 40°. At this time also there was fog in the valley. Moreover, it was observed that the temperature of the air on the summit began to rise after midnight, being 51° at midnight 12th September, and 53° at 7.0 a.m. the following morning.

The figures quoted above show that in the late summer the top, even of a mountain of appreciable height, is warmer during clear still nights than the valley bottom beneath and that this is because the air over the surface of the ground is cooled by radiation and flows downhill, filling up the valley. Exactly the same thing happens in the spring, or at other times of the year, and where the ground rises to a considerable height above the valley bottom, as in many places in the Highlands, the depth of the cooled air in the valley must sometimes amount to several hundred feet. Thus an early morning observation of Cohen on Coniston Old Man showed only the summits of the mountains rising above the mist filling the valley, the level of the mist being an indication of the height to which the cooled air had risen. It is because of this that the upper slopes of valleys have become well known as being warmer at night and more frost free than the lower. Where the top of the hill is a plateau and, therefore, flat, this warm zone of the upper slopes does not extend to the summit, from which, owing to its flatness the cold air is unable to drain away. Any level areas, such as the flat shelves which sometimes occur on hill-sides, hold the cold air in this way, producing local areas where frost injury is especially liable to take place, as is shown. Map 8 (page 122), of part of Inchnacardoch Forest, near Fort Augustus, provides such an example.

Effect of Ground Cover on Drainage of Air.

The surface of the ground has a braking effect on the movement of air flowing over it. Even on bare ground a wind blows less strongly just over the soil than a short way above it. Any vegetation increases this effect, largely in proportion to its density and height. In a forest the ground is rarely if ever bare. On the more recently regenerated parts, which are those most subject to severe frost damage, the ground cover is usually a mixture of herbs and small trees. As this gradually increases in height and density, the rate of movement of air within it decreases until eventually, with closed canopy, one gets the quiet stillness which is typical of dense woodland. It follows that, even on the warm upper slopes of a hill-side, the effect of a ground cover of young trees, before the canopy is formed, will be to slow up the rate of movement of the air within, and if it becomes dense enough, to stop it altogether. This will create a deep layer of cold air liable to cause frost injury which, however, does not often occur to a serious extent because the tops of the trees will generally be above it.

The braking effect of vegetation on the movement of air draining down a slope is seen most markedly when woodland, or even a belt of trees or only a hedge crosses a slope. If sufficiently dense, these cause such an obstruction that the downward moving air is pooled up behind them, with the result that a local frost zone is created on the hill-side. Every obstruction crossing a slope acts in this way. It is important, therefore, to remember that if hedges or belts of trees are left for shelter they should run up and down the slope and not across it.

INFLUENCE OF TOPOGRAPHY ON THE SEVERITY OF FROSTS.

The severity of the frost in any particular place is very largely determined by the physical aspect of the countryside. A detailed discussion on this matter, in relation to situations which differ in topography, is given in Appendix II (page 114). Here, a summary statement is made of some of the more important points.

The length, steepness, and aspect of a slope affect the local climate in several ways. Aspect is important chiefly in relation to the amount of sunshine received. Thus a northerly aspect is colder than a southerly, while an easterly one receives morning sun whereas a westerly one does not. Slope is important in that its steepness partly regulates the amount and intensity of sunshine received: thus a steep northerly slope receives less sunshine than one that is less steep, and is, therefore, colder. Slope is also important in that it regulates the drainage of cold air. The longer the slope, the greater will be the amount of cold air draining into the valley; the steeper the slope, the more rapidly will this drainage take place.

It has usually been accepted that the easterly and southerly aspects are the most dangerous as regards frost damage, because they either receive the morning sun first, or are the warmest. The early sun results in quick thawing, which tends to increase the severity of frost damage; while on the warmer aspects plants begin growth earlier than on the colder, and thus come earlier into a tender and frost-susceptible state. This is probably true on the average, but actually a good deal of variation is found from what one might expect. Thus in the fruit areas of Kent[4] the westerly aspects suffered most, and then the southerly, from the May frosts of 1935, while a summary of 47 reports received from State forests all over Britain showed that northerly aspects suffered most and southerly aspects least. Results such as these appear contradictory because it was impossible to analyse with sufficient accuracy the factors which affect either the stage of development of the plants, or the severity of frost in any particular place. Soil and weather conditions, and the state of the plants at the time of freezing, all have to be taken into account.

The study of these things is of great importance in considering liability to severe frosts, but certain general rules depending on topography may be stated.

For convenience of discussion a number of topographical types may be recognised. The plain and plateau, or elevated plain, provide situations in which severe ground frost is liable to occur owing to the inability of the cold air, which forms over the surface of the earth on clear calm nights, to flow away. This layer of cold air is not usually very deep, but it is usually sufficient to cover the smaller trees. The severity of the frosts is considerably affected by the condition of the surface of the ground (*see* pp. 16–17). The Breckland in Norfolk and Suffolk, and the flat tops of the Chiltern or Cotswold Hills provide examples of this type of situation.

The broad valley is a very similar topographical type and, indeed, a broad flat valley bottom is a plain, though sometimes of rather limited extent. It is, however, a plain on to which cold air may drain from the surrounding hills. The depth to which severe frost damage is liable to occur tends thus to be increased, but much depends on the width of the valley and the height and slope of the hills. Many examples of this type might be given, but the valleys on the Weald Clay in south-eastern England and in Dorset are typical.

The situations least subject to spring frosts are provided by the tops and upper slopes of hills or mountains from which cold air can drain freely. In certain districts, for example in Mortimer Forest, part of which is in Shropshire, an important topographical type of this kind is provided, and there is no evidence of really severe frost damage occurring on them during recent years. Flat hilltops are really small plateaux and are frosty places.

Some of the most important topographical situations, from the point of view of forestry, are to be found on the sides of valleys. A distinction has to be made between valleys in lowland hills, which can be afforested to the hilltops, and those in the higher mountains where the limit of economic tree growth does not reach to the summit. Valleys of the former type are to be found in the Chiltern Hills, the Yorkshire Moors or the foothills of the Grampians; those of the latter type occur in the mountainous districts in the western and northern parts of Britain.

In the lowland valley the upper slopes are markedly free from severe frost injury, as may often be observed in the beech woods of the chalk hills, or the oak woods of the Forest of Dean. The severity of frost damage increases towards the valley bottom. In the mountain valley, however, the whole forest is commonly situated on the cold lower parts of the slopes, the warm upper part being above the planting limit, and the afforested slopes show more severe frost damage than in the lowland valleys.

The degree to which cold air fills up a valley depends chiefly on the valley's width, straightness and steepness. It is also much influenced by the sort of place on to which the valley debouches. Thus a wide, straight, steep mountain valley which opens on to the sea, or a wide plain, is much less likely to suffer severely from frost than one which is narrower, more crooked, flat bottomed, and opens on to another narrow valley. Examples of this are given in detail in the discussion in Appendix II (page 114). Taking these things into account one may say in general that in the mountain valley the most severe frost will occur at the bottom, but that where the tops are high above the limit of afforestation, the upper part of the afforested slopes will be much less free from severe frosts than the lowland valley.

Hummocky areas consisting of little hills and valleys often provide localities which are difficult to deal with. Each little valley acts as a frost hollow, the hilltops standing out as comparatively warm islands.

Any flat place or slight depression on a slope acts as a frost pocket, irrespective of its elevation. Gentle slopes, even when high above the valley bottom, may also be subject to severe spring frosts. This is accentuated when they are covered with shrubby vegetation.

The height to which trees are liable to be injured depends chiefly on the height to which cold air is able to accumulate at night. Thus on a wide plain it will be comparatively shallow, while in a deep narrow valley it may rise much higher than the tallest tree.

Silvicultural considerations are dealt with elsewhere, but it may be noted that where the layer of cold air is shallow it is often possible to create a favourable climate for the growth of small trees by regeneration under shelter, whereas when the cold air is very deep, as in a narrow valley, this becomes difficult or impossible.

NATURE OF LATE FROST INJURY TO TREES AND SHRUBS.

A great deal of work has been published on the mechanism of frost damage, and the fundamental causes of frost resistance. There is no absolute agreement on this matter and it will not be discussed here. Chandler[7], Harvey[21], Rosa[39] and Maximov[26] give useful summaries of the work that has been done on it. No internal factor which can be used as a reliable indicator of frost-hardiness has been found. In view of the difficulty of extending refrigerator experiments to cover a large number of species, a frost such as that of May 1935, is the only means available of comparing the susceptibility of the majority of common trees, and as such may be regarded to a limited extent as a blessing in disguise.

Before considering the types of damage which occurred, it is necessary to understand why a plant which can withstand the rigours of winter should be damaged by lesser frosts in May. The generally accepted explanation is that the plant is more tender in May, meaning not so much that it is more susceptible to frost, but that it is actually softer and, therefore, it is presumed, more liable to damage. This is only very partially true. In the winter a tree is hardy primarily because of the condition of the cell sap. It is known that during the spring some change in the sap takes place, rendering the plant more liable to frost injury, and that in the autumn the process is reversed so that the plant becomes hardy again. While, as has been pointed out above, the chemistry of this change is not fully understood, its effect on the susceptibility of the tree to frost has been investigated[13, 47]. So far as is known at present the susceptibility of most trees grown in Britain is lowest in December and January; from mid-February onwards it rises until the end of May, or early June; throughout the summer it remains more or less constant, and during October and November it falls again to the winter level. This is shown by the curves in Fig. II, which illustrate the rise and fall of susceptibility for, (a)

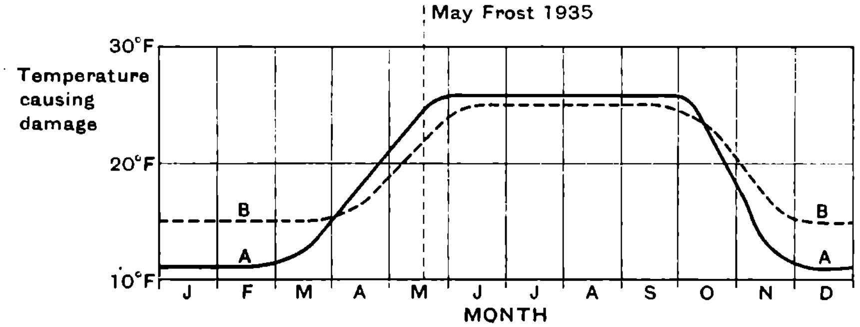


Fig. II.—Diagram illustrating variation in susceptibility to frost damage throughout the year for (A) a winter-hardy and spring-susceptible tree, and (B) a winter-susceptible and spring-hardy tree.

a winter-hardy and spring-susceptible tree and (b) a winter-susceptible and spring-hardy tree. It will be seen that while in the winter a lower temperature is required to damage "a" than "b", the reverse is the case in May. Sitka spruce may be taken as a good example of "a" and *Cupressus macrocarpa* of "b". Besides these two types there are trees and shrubs which are hardy at all periods, such as birch or elm, and those which are susceptible at all periods, such as fuchsia or hydrangea. The exact form of the curve for susceptibility will not only vary from species to species, but also from race to race, and even among individuals. In late and early flushing races of any species, such as exist in Norway spruce, the relative susceptibility in the winter and the summer is the same, the only difference lying in the fact that the late trees are behind the early in development and, therefore, in susceptibility during the most critical months of the spring (Fig. III).

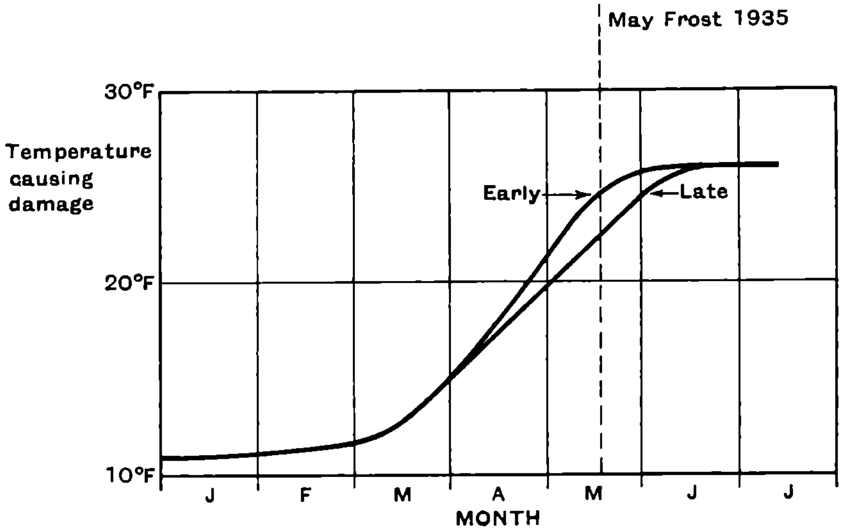


FIG. III.—Diagram illustrating differences in susceptibility in the spring between early and late flushing races of the same tree.

If the generally accepted idea that the unflushed tree is hardy and the flushed tree susceptible to frost were wholly true one would expect to get a particularly rapid rise in the curve at the time of flushing. So far as can be ascertained experimentally this does not in fact occur. In April and May the susceptibility rises steadily but more rapidly than in March. It will be seen that owing to this rapid rise in susceptibility, a very slight difference in time of development makes a very large difference in liability to injury. Thus though the curves in Figs. II and III are not separated very much in time, *i.e.*, on the horizontal axis, in May they are very widely separated in susceptibility, *i.e.*, on the vertical axis, at the point where the line representing the mid-May frost crosses them. Thus difference in time of flushing between two trees of the same species is only of importance in so far as it indicates that one tree is further developed and, therefore, more susceptible than the other. Such differences between trees of different genera are of practically no importance, for instance elms flushed, as all elms must be, in mid-May proved much less susceptible than ash trees, which were still in the bud stage.

It has been frequently suggested that certain resistant genera such as birch, or resistant individuals among such species as oak, escaped because they had time after flushing to harden before the frost. There are several difficulties about this explanation, in the first place it ignores the fact that no tree will have stopped growing as early as mid-May, and that therefore, even though the basal parts, and older leaves on the young shoots may have become "harder", there is still a young growing point, and tender, freshly formed leaves associated with it. Secondly so far, there is no experimental evidence of a fall in the temperature required to produce frost injury on a tree after the foliage has reached its maximum at the end of May or beginning of June, until the leaves start to fall again in the autumn. It must be presumed, as seems perfectly reasonable, that difference in susceptibility between different species, well advanced in growth, and between individuals of the same species in the same state of development is due to differences in the state of the cell sap. There is, however, always the possibility that in some species the earliest trees may be of a particularly hardy strain, but there is no evidence to support this other than the repeated statements in reports, especially with regard to oak, that the trees that had been some time in leaf escaped more lightly than those just breaking. Thus the amount of damage suffered by a tree in mid-May frosts is related to two factors: first, inherent susceptibility and secondly, stage of development and the correlated state of the cell sap.

There is this much support for the use of the word "tender", that certain parts of the tree are much more susceptible to frost damage than others, and before considering the types of injury occurring it is necessary to know what these parts are. In general any part that is growing or about to grow or has just ceased to grow is liable to injury. The most obvious of these are the young shoot and leaves and indeed these are perhaps the most easily damaged parts of the plant. The bud before it opens is also easily damaged, and more important still, so is the cambium. The cambium is the layer of actively dividing cells situated on the surface of the wood under the bark. It is this layer which by forming cells on the inside, produces the wood, and on the outside the phloem or food-conducting tissue. The cambium becomes active in the spring before the buds have burst. Its activity, in most trees at any rate, starts in the buds, and spreads rapidly down the twigs and branches to the trunk[33, 35]. Thus the tips are susceptible before the lower parts of the twigs, and the twigs before the branches. In addition to the young developing shoot and the cambium all the living tissues in the shoot such as the pith or the bark are liable to damage.

The injury caused by frost on trees and shrubs may be conveniently considered under four headings according to the parts damaged, namely leaves, young shoots, buds and old wood.

(*i*) *Injury to Leaves.*—In its mildest form only a part of the leaves is injured. In broadleaved trees the edges of the leaves shrivel, or often only patches of the leaf are killed, and a mottled effect results. In conifers the tips of the needles may be damaged; this is a particularly common form of injury in larch. Damage of this kind has practically no effect on the health of the tree and very little on its appearance. If the whole of the leaf or needle on the young shoot is damaged injury will almost certainly extend to the shoot itself and such injury, therefore, really belongs to the next section. When the young leaves or needles are entirely shrivelled by frost they tend to hang on the tree for some months, presumably because the abscission layer which is formed when the leaves are shed in the autumn, has, naturally, not even started to form. These remarks on damage to young leaves apply equally to evergreen and deciduous trees; but in the case of evergreens we have also to consider damage to the older leaves. These are never more, and often less susceptible, than the young leaves, and it follows that damage to them will be accompanied by damage to young leaves. If, some time after a frost, a tree is found in which the old leaves have been damaged, but the young are unhurt, it can be assumed that it had not flushed at the time of freezing. Damage to the old needles alone was found in spruce and pine, though in the case of the former there was some confusion with the injury due to the green spruce aphis *Neomyzaphis* (*Aphis*) *abietina.* When the old needles of conifers are injured they turn brown and fall off quite soon, so that a few weeks after the frost the bareness of the old stems is the only sign of the damage done. Of course when the old wood on an evergreen is damaged, as happened in a great many cases, the leaves on the injured portion are also affected.

(*ii*) *Injury to young Shoots.*—The most frequent form of damage in the frosts of May 1935, was undoubtedly that to the young shoots. In most cases the whole shoot, but sometimes only the tip, was affected. Where damage of this nature took place the shoot collapsed, changed colour and hung for some time on the tree in a withered condition. The amount of tissue affected depended of course on the development of the tree, and might vary from shoots over a foot long on trees such as early ash, to shoots less than an inch long just emerging from the buds. It was damage to these shoots and the leaves that had been formed on them that was responsible for most of the unusual colour effects visible after the frost. The browning of the beeches, the blackening of the ash and oak, and the curious cream colour of box were all due to degenerative colour changes in the frosted shoots and leaves. Damage of this nature is shown in Plate I, figs. 1 and 2; Plate II, fig. 1, and Plate III, fig. 1.

(*iii*) *Injury to Buds.*—This is really the same as the damage described in the previous paragraph but takes place when the tree is in an earlier stage. Those buds that are about to develop into shoots tend, as has already been stated, to be in a more advanced condition than the twigs on which they are situated. Damage to the buds alone is, therefore, possible, and did in fact frequently occur. This type of damage in ash is illustrated in Plate III, fig. 2, where the terminal buds, which would have formed shoots, have been killed, and buds which would normally have remained dormant have developed. These dormant buds do not normally become activated in any way in the spring, for usually they would not develop shoots. Therefore they are no more liable to damage than the old shoots on which they are situated. Damage to buds is usually not at all striking, as it results in a slight retardation of flushing, although occasionally there is a tendency for forking and crooked growth. Mention should perhaps be made here of the conifers such as *Thuya* and *Cupressus* which form no resting buds in the winter, and the broadleaved evergreens such as ivy, *Viburnum tinus*, and *Buddleia globosa* on which no terminal buds are formed. Naturally damage done to these can only fall into the other three classes, namely damage to the leaves, to the young shoots and to the old wood. Exact distinction between the last two is apt to be rather difficult, owing to the fact that there is no definite cessation of growth during the winter.

(*iv*) *Injury to old Wood.*—Naturally this is the most serious type of injury that can occur to the tree. Injury of this nature is shown in Plate IV, fig. 1. Old wood is less susceptible to frost than the young shoots and the active buds because it tends to be slightly backward in cell activity and because it is better protected by the bark. The farther one goes down the tree the more backward is the cell activity and the thicker is the bark; so that, in general, the ends of the twigs are more liable to injury than their lower parts, the twigs than the branches, and branches than the trunk. Thus when the old wood in a tree is killed the outer parts tend to suffer more than those nearer the root, and the more severe the damage the nearer to the base of the tree does the injury extend causing finally the death of the whole tree. The cambium on a main branch first becomes active where a minor branch joins it, and consequently tissue at the insertion of branches becomes frost-susceptible before that surrounding them. If the active cambium at these spots is killed by the frost a canker will result owing to the efforts of the surrounding live tissue to heal over the wound.

In making the statement that the old wood in general becomes less susceptible to damage as we pass downwards it has been assumed that the whole of the tree is exposed to the same temperature. In actual fact this is often not the case. It has already been made clear that the bottom of the tree may be exposed to greater cold than the top. This tends to some extent to nullify the benefits that the basal parts of the tree gain from their relative backwardness and thicker bark. Sometimes particularly low temperatures occur among the tips of the herbage and in a small tree the cambium may be killed at that level and not above it. If this happens the top of the tree remains alive for some time, and may make a certain amount of fresh growth. It is only in the latter part of the season that the top dies, and the damage becomes apparent. Damage of this kind has been specifically noticed in Scots pine, but probably occurs quite widely. Neither this kind of injury, nor that of cankers resulting from the death of small portions of the cambium, is apparent till some time after the frost, and at the time the reports on the May frosts of 1935 were sent in it was not possible to say to what extent they had occurred. In places where late frosts also occurred in 1936 the cankers may develop seriously, for the cambium on the edges of the canker would no longer be protected by bark, and would tend, in its efforts to heal the wound, to start growth activity earlier than the cambium around it. For these two reasons a canker is particularly liable to damage, and if fairly severe frosts occur for several years running it may spread rather than heal and eventually girdle the branch or stem on which it is situated. Once frost has started a canker, several seasons more or less free from severe frost are required before it can heal again.

Though death of the cambium is required before the results of injury can become visible externally, the cambium can be injured without being killed. So far as is known this type of injury does not appreciably affect the health of the tree, resulting as it does only in the formation of abnormal wood cells in the earlier part of the season's growth. These " frost rings " as they are called can now frequently be found in twigs, as a result of the frosts of May, 1935. They form the most valuable means of frost diagnosis.

Naturally the older the tree the less liable are the trunk and branches to injury by May frosts. For one thing the bark is thicker, and for another the outer parts of the tree tend to protect the inner from loss of heat by radiation and, therefore, from injury. For this reason the larger the tree, the less common do cankers near the base, girdling of the stem, and considerable or total dieback of the tree become. While the initial effects of the 1935 frost were more apparent on large trees, because of their size, the actual damage was much more serious on small trees and the final effect on large trees has not been at all serious (Plate IV, fig. 2). The type of damage occurring on large trees is illustrated by Plate III, fig. 2, where it can be seen that dying of buds and twigs, that might severely cripple young trees have had no serious effect.

No specific mention has been made above of damage due to cold winds. Practically nothing is known of the mechanism of such damage, or how, if at all, it can be distinguished from that due to frost alone. Lacking this, it is only possible to come to any decision as to the cause of the injury from the position of the tree, and of the damage on it. Only in one area—in Scotland near Inverness—was damage seen, which, as it was confined to the seaward side of the tree, seemed to be almost certainly due to the cold winds. In broadleaved trees the edges of the leaves were affected and in conifers the end of the needles. A number of reports of damage confined to the north-east sides of trees in exposed situations was received, in which the damage may have been due to this cause, but no particulars of the type of injury were given.

Recovery from Injury.—Having reviewed the types of injury that occur on trees and shrubs as a result of late frost, it is now necessary to consider briefly the means whereby the tree recovers. Naturally the method of recovery will vary with the amount of damage done, but in most cases it is based on the production of shoots from buds which would otherwise have remained dormant or developed later, and on the production of buds and subsequently of shoots where normally no growth would have taken place. If damage is confined to the leaves normal shoot growth continues, and no special recovery shoots are formed. If only the tips of the young shoots are killed, the buds in the axils of the leaves near the end of the live portion sprout, and the only result is forking of the young shoot. If, as in most conifers, there are no such buds in the leaf axils, the shoot tends eventually to dieback to the base, and recovery, therefore, to proceed as if the whole shoot had been killed in the first place by the frost. If the whole young shoot or the unflushed terminal bud has been killed the dormant buds nearest the tip of the previous year's shoot become active and form new shoots. These dormant buds would normally remain inactive, gradually lose their vitality and be cast off. Various explanations have been put forward to account for their dormancy; one of the most reasonable is that recently advanced by Priestley[34], who suggests that the buds which develop have a more direct connection with the water-conducting system of the plant, and that the other buds are kept inactive by lack of water. When the developing bud or tip of the shoot is removed by death or by pruning, the dormant buds nearest the tip of the shoot can avail themselves of the accumulating water, and are thus able to grow. The number of dormant buds present varies very much from tree to tree, and in general there are fewer in the conifers than in the broadleaved trees. Naturally the better furnished a tree is with dormant buds the easier is its recovery from frost damage.

In the case of those conifers already mentioned, which do not form resting buds in the winter, recovery takes place by the growth or development of axillary shoots, many of which are always present, but which normally make little growth. In the case of broadleaved evergreens which form no terminal buds during the winter, recovery shoots will be produced from dormant axillary buds, which are normally formed.

If much of the older wood has been killed the remaining live parts owing to their age may be lacking in dormant buds, and then the tree has to produce buds anew. The capacity to do this varies very much in different trees, and again broadleaved trees as a whole are better able to produce new buds than conifers. In fact with many broadleaved trees death by a single frost is almost impossible, as even if they are killed down to the root collar fresh sucker shoots will arise from the roots. The great majority of conifers do not possess this capacity and are, therefore, more frequently killed by frost.

From the point of view of the tree, recovery may be considered as satisfactory if the tree can produce sufficient fresh shoots to replace those that were lost. From the forester's viewpoint the outstanding necessity is the maintenance of a leading shoot. It is for this reason that, in conifers particularly, damage to leading shoots is considered of much more importance in estimating the severity of injury, than that to side shoots. With regard to the leading shoots of conifers it may be mentioned here that they are usually later in flushing than the terminal buds on the side shoots. The reason for this is not known, but it has the effect of rendering the leaders less susceptible to frost injury and, therefore, tends to preserve the most important bud to continue uninterruptedly the upward growth of the tree. In certain cases this has reacted to the temporary benefit of the tree, as the side shoots being killed, all the reserves have gone into the leader and its growth has been unusually vigorous. If the leading bud or young leading shoot is killed, some other shoot must take its place. In most broadleaved trees there is seldom a very definite leading shoot in the first place, and its loss is not, therefore, of much importance, but in most conifers, and in some broadleaved trees such as ash, there is a definite leading shoot and if it is killed others arise to take its place. Usually they come from the topmost buds on the undamaged part of the main axis of the tree (Plate I, fig. 2). Sometimes one of the more vigorous branches takes the place of the original leader, as is shown to be the tendency in Plate IV, fig. 1. In many cases two or more shoots may attempt to take the leader's place and forking results. It will be seen that, however the new leader arises, it will have a tendency to crookedness at the base; unless this is very slight, it will persist as the tree grows larger, and will eventually spoil the straightness of the stem. In some ways, if the tree is small, a better final shape is produced if it is cut back to the base by the frost and an entirely new shoot system has to develop.

It is obvious that frosts repeated year after year will, by causing the same type of damage again and again, tend to increase the abnormalities of growth form resultant on recovery. Thus if the young shoots are continually cut back so that several buds at the base of them develop the tree will tend to become full of small branching twigs, and present an unnaturally bushy appearance (Plate V, fig. 1). If more severe damage is repeated for several years the trees will become merely a mass of dead twigs with small weakly recovery shoots in the lower parts, and will eventually die (Plate V, fig. 2). For while, after one frosting, the shoots formed in recovery can be extremely vigorous—for instance some young tulip trees planted in 1931 and cut to the base by the frosts of May 1935, formed in a single season recovery shoots equalling the original height of the tree—each year the tree is frosted, recovery tends to become more feeble, until, even a species like spruce with amazing powers of resistance to repeated frost prunings, eventually dies.

As regards the factors affecting injury to the tree a clear distinction must be drawn here between those, such as shelter and topography, which primarily affect the temperature, and consequently the severity of injury, and those appertaining to the tree itself. Naturally the state of development of the tree is a very important matter in determining the amount of injury, but two other factors remain, the health and the size of the tree.

At first it might seem that an unhealthy tree would be worse damaged by frost than a healthy one, on the well-advertised principle that a strong constitution is resistant to disease. This is far from being the case. The healthy tree will make a far better recovery, after having been damaged, but it is more susceptible to damage in the first place. This is due to the fact that the unhealthy tree tends to be backward. This is best illustrated by the spruces. Spruce after planting, particularly on poor sites, is liable to go into check, *i.e.*, for a number of years it makes practically no growth. While in this condition what growth there is starts very late and the plants escape damage unless the frost is sufficiently severe to injure the old wood. Transplanting has the same effect ; it was very noticeable that young trees planted in the winter of 1934–35 were not usually so much damaged as plantations that had become established and, therefore, able to make growth earlier in the spring. This same effect was also noticeable in the nursery, where plants that had been moved the previous winter tended to be more backward, and therefore hardier than those which had not been moved. A very good example of this is given under *Fagus*, in a later section.

The size of the tree affects its susceptibility and powers of recovery in various ways. As regards recovery the large tree has an obvious advantage. It has larger reserves to draw on and more dormant buds from which to produce shoots; also, the loss of say one inch from all the shoots of a tree fifty feet high would bear a much smaller relation to the whole bulk of the tree, than it would in a tree one foot in height. Therefore the same actual amount of damage is relatively less serious on a large tree.

The most important effect of size or rather of height in the tree is to raise its topmost branches out of the coldest air near the ground. It is very noticeable in the detailed counts made in various forest areas that, in nearly every case, where height had any effect on damage at all, the taller trees were less injured. There were a few exceptions to this, but in some cases there is reason to suppose that the smallest plants were sheltered by coarse herbage. Of course if all the trees in a plantation were in the layer of the coldest air, as was often the case, the taller trees had no advantage. Nevertheless the larger the tree the greater the possibility that its most important part—the leading shoot or the top of the crown—will be in warmer air, and thus escape injury or at any rate be less severely damaged (Frontispiece and Plate II, fig 2).

OCCURRENCE, DISTRIBUTION AND RELATIVE SEVERITY OF THE MAY FROSTS, 1935.

Information as to the occurrence of the 1935 May frosts has been collected from various unofficial sources as well as from the records of the Meteorological office[1,2]. This information is set out in full in Appendix I (page 110), where notes on the less important frosts of May and early June, 1935, are also given. So varied was the incidence of the frosts and so diverse the weather conditions accompanying them that no summary of these data is possible. It must suffice to say that the nights on which the frost was most generally severe were the 15th, 17th and 18th of May, and that the wind throughout the frosty period, which lasted from the 13th to the 22nd, whatever its direction, was always of polar origin. The speed of the wind and the amount of cloud were not only variable from night to night, but also from place to place on the same night, and rain, and in some places snow, occurred more than once.

As regards the distribution of low temperatures over the whole period, the country can be divided into areas of three grades: those where the frost was really severe; those where it was only moderately severe, and those which escaped lightly. Owing to local variations in climate many small areas were exceptional to the main area in which they lay and in any case the boundaries of the various areas can only be indicated very approximately. These boundaries are shown on Map 2 (page 42). Cornwall, Devon, Dorset and south Hampshire, including the Isle of Wight, form the first of the areas which escaped lightly. No really low temperatures were recorded and on many parts of the south coast there was no frost at all. North of this was an area bounded by a line drawn from the Wash to Aberystwyth, most of which was subjected to very severe frosts. Various examples are quoted in Appendix I of low temperatures recorded in this area, particularly on the 17th and 18th of May. North of this again was an area, bounded by a line drawn from the Humber to Morecambe Bay, which escaped comparatively lightly. Here there were a few stations where quite low temperatures were recorded, and in other places, as for example some of the valleys in north Wales, the temperatures must have been low. Most parts of this area, however, had only slight frosts, and no exceptionally low temperatures were recorded. The Isle of Man, which suffered practically no frost, should perhaps be included in this area. To the north again was an area bounded on the west and north by a line drawn from Wigtown to Glasgow, and thence to Edinburgh. This is the second area where temperatures were outstandingly low, though no temperatures were recorded as low as some of those in the southern half of England. This was the area so predominantly affected by the frost of the 15th. The western seaboard of Scotland as far north as Loch Torridon, the Highlands as far north as Fort Augustus and Kingussie, and the eastern seaboard as far north as Aberdeen come into the second category, areas where the frost was moderately severe. Quite low temperatures were registered in many places, a grass minimum of 16° F. in Argyll, and a screen minimum of 21° F. in the central Highlands, but there were not many outstanding records, and many places, particularly along the coast, had only slight frosts. That part of Scotland which faces north across the Moray Firth, and western Ross and Cromarty contains what was perhaps the most outstanding area of escape from the frost. At the eastern end of this area there were moderate frosts, but at the western end round the Moray Firth proper there was very little frost at all. It is suspected that this area of little frost extended along the east coast as far as Wick. For the rest of the mainland of Scotland, *i.e.*, the northern Highlands, there are no temperatures whatsoever available. In the Western Isles and Orkney there was very little frost indeed, and in Shetland there was only a screen minimum of 28° F. on the 17th. The Isles thus formed another of the areas which escaped lightly.

If we consider the mass of rather incoherent data set out for each night in Appendix I a number of points emerge, which seem worthy of further consideration and may in part explain the curiously erratic effects of the frost. First we have the fact that there were so many frosts. Many of the more frosty localities must have experienced five or six frosts, and two or three must have been really severe. There is considerable evidence that repeated freezing and thawing is bad for a plant and there is little doubt that two or three severe frosts are likely to do more damage than one.

Then, the wind was not, as was so generally supposed, in the north-east throughout the whole period. In the night of the 16th–17th, that of the most generally severe frost, it was in the south-west, as it was also on the night of the 14th–15th in an area which then suffered its most severe frost. On the night of the 17th–18th, the other night of important frost, the winds were generally northerly. Thus many places must have been subject to cold air moving from the south-west on one night and from the north or north-east on another. These variations in the wind may well explain some of the problems which occur over questions of shelter, aspect, etc. It must not be assumed, as was pointed out above, that the direction of the wind had any major effect on its temperature. During the period of most severe frosts the south-westerly winds were merely deflections of the cold northerly air current coming from polar regions. The northerly winds at the beginning and end of the frosty period were not so cold, because they did not come from so far north.

We have also the fact that during the frost period the weather was fine to cloudy over so much of the country. Only rarely were there cloudless or semi-cloudless skies for more than two or three hours, and there is no doubt that surprising differences in frost between places quite close together were due not only to topography but also to variations in the amount of cloud passing over them during the night.

Throughout most of the period there was comparatively frequent rain, and in the west and north, snow. Apart from its effects on the temperature, this may well have affected the amount of damage. Our knowledge of the effect of damping a plant before or during freezing is very incomplete, but there is evidence that under some circumstances it increases the amount of damage. Snow, on the other hand, in the few areas where it fell sufficiently heavily, may well have acted as a protection to the lower parts of the plants; though above a snow-surface temperatures are likely to be lower than above bare ground or vegetation, because snow, acting as an insulating layer, stops the escape of heat from the ground to the air.

The speed of the wind must also enter into our consideration of damage during this period. In general, light winds are to be dreaded because they fail to prevent the formation of pools of cold air; higher winds do and so help to prevent the temperature of the air near the ground from falling dangerously low. There is evidence in some places of damage due to cold wind rather than directly to frost. It is very doubtful, in these cases, to what extent the wind or the cold respectively is responsible for the damage.

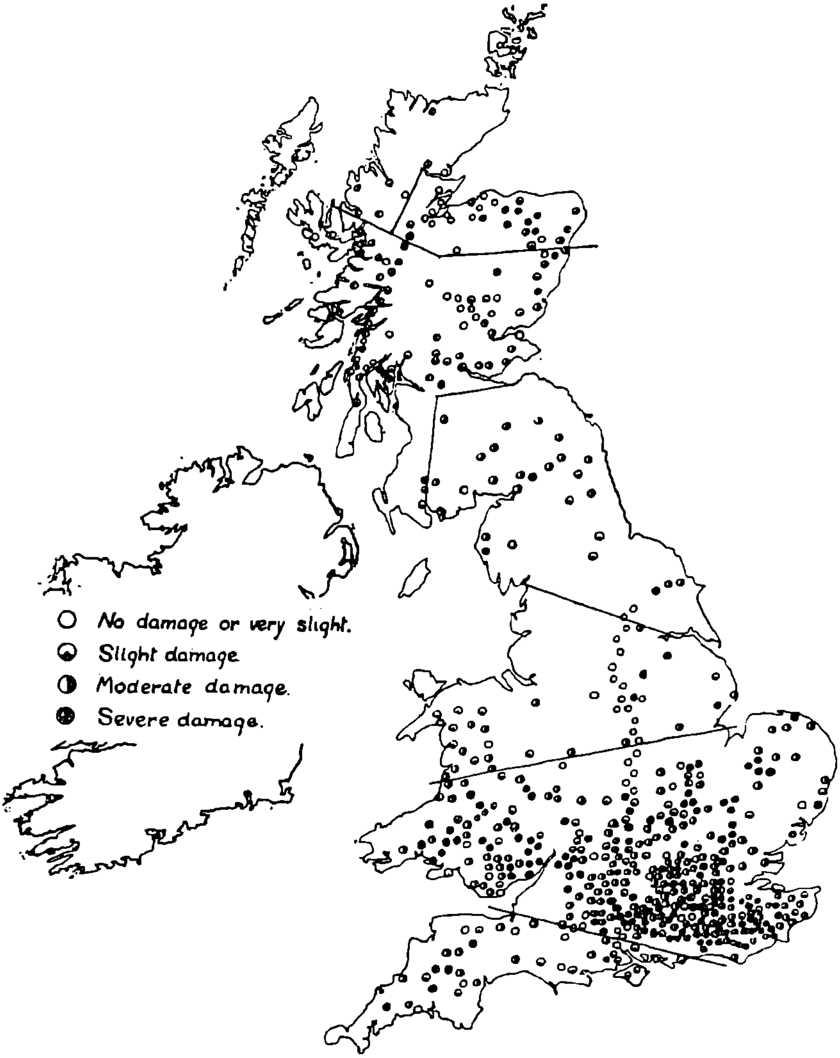
Apart from the general lowering of dew-points on 12th May and the general rise which took place on the 19th, there is no obvious connection between the dew-point and the degree of low temperature recorded. Local dryness of the air, with consequent low dew-point, does not seem to have much affected the minimum temperature, or, if it had any such effect, this was masked by the much greater effect of wind and cloud.

On all nights but that of the 17th–18th, these frosts form a very clear illustration of the rule that damagingly low temperatures are especially likely to occur in May when the wind is sufficiently light and the sky sufficiently clear; it should not be overlooked, however, that the basic cause of the whole period of frosts was the current of cold air from the north, and had this been absent and, therefore, the general air temperature been higher, however clear the sky and however low the wind, such devastating frosts could not possibly have occurred.

The conditions under which thaw took place after the various frosts were far too variable to permit of analysis; there were sun, cloud, rain, snow, singly and in combinations. Nevertheless, under some circumstances the rate of thawing affects the amount of damage to the plant, and may help to explain differences in damage in different localities.

It is obvious from the above that exactly to correlate meteorological conditions with the amount of frost, and with the effect of that frost on the vegetation, detailed study of a representative number of areas, each equipped with a complete meteorological observatory would be required. In the circumstances it has been possible to discuss only general considerations and to draw general conclusions, and to direct attention to many apparent anomalies.

An attempt has been made on Map 2 to indicate, so far as it is known, the severity of the damage caused by the 1935 May frosts. Each marking on the map is based on information received or collected from a single observation point, though in certain cases such areas were very closely adjacent. This attempt is fraught



Map 2.

Map illustrating the distribution of damage caused by the frosts of May 1935.

with difficulty for a number of reasons. In the first place the data on which an estimate of severity can be based, are, for a large part of the country, very inadequate and in some instances biased. Secondly, owing to variations in local climate, very different degrees of severity can be found in places immediately adjacent. Thirdly the majority of the entries on the map were not made as a result of personal observation by one man, but as the result of estimates based on reports, often incomplete, of the injury occurring in the places concerned. Only in a few cases did the same person report on more than one area, and for this reason alone the data can hardly be regarded as comparable.

The information on which the map is based was gleaned almost entirely from three sources. The first was reports from the State Forest areas, the distribution of which is very irregular, being dependent to a large extent on the distribution of land suitable and available for afforestation. In Scotland large areas in the northern Highlands, in the centre of the southern Highlands and in the counties south of Glasgow, and in England a broad belt stretching from Lancashire through the Midlands to Essex and Kent are more or less untouched by these reports. The second source was some three hundred letters received in answer to an appeal published in "*The Times*" asking for information. Most of these came from the home counties, but a few were sent from Wales, north England and Scotland. It was also obvious that they had in the main come only from districts where damage was severe, or striking to the eye. This was particularly noticeable in Hampshire, for nearly all the large number of letters received from that county came from the northern half; the New Forest, and the coast, which escaped lightly from the frost, produced very few. The third source of information was notes taken during personal visits and journeys made soon after the frost. Journeys with Oxford as a centre were made to Chiddingfold in south-west Surrey, to Stourhead in south-west Wiltshire, to Cambridge and to York, and notes were also made in the course of a trip round central Scotland. In certain cases observations were confined to what trees could be seen from a car or train and, therefore, only cover a very small sample of the country passed through. These personal notes and the Forestry Commission reports, in that they refer also to places where no damage occurred, do not suffer from one of the disadvantages attached to the letters, which usually did not report the places which escaped injury.

It was impossible to find in the various sources of information any generally occurring tree, or trees, the damage to which could be used as a "severity index" for the whole country. Naturally the estimates of severity were based largely on the amount of damage to the commoner species of trees, but an estimate of damage in one area might depend mainly on reports of injury to oak and ash, while in another it might be based mainly on that to spruce and larch. In general estimates of severity have been based on the amount of damage to fairly frost-susceptible trees such as those just mentioned, lack of damage to particularly susceptible trees such as walnut, or the presence of damage on particularly resistant trees such as elm being given their due weight. In districts where resistant trees predominate the damage was naturally less striking than in those where susceptible species are predominant. This is a possible source of error in estimating degree of damage, for a report may well mention devastating injury to the susceptible trees, without stating that most trees in the district are resistant. There is also considerable difficulty in comparing damage to the small trees in recently established plantations with that to large trees.

It will be understood from the above that on examining the map on page 42 no importance should be attached to a single entry, except in so far as it indicates, if it is one of the markings showing damage, that frost injury did occur in that area. Only by a visual summation of a number of markings can any estimation of the damage in a given area be made. This unfortunately means that in a large number of areas we have really no idea how much damage was done by the frosts. In considering the markings on the map, it must be remembered that the density of the dots has no significance, as regards severity of damage, except in parts of the south of England, where it serves to some extent as an indication of those districts most obviously affected by the frost. The important matter is the amount of damage indicated by each marking. As the map is already divided into areas based on the minimum temperatures experienced, and as the amount of damage in different parts of the country should bear some relation to these areas, it will be convenient to consider the amount of injury in each of them separately.

Section (i), South-west England.—In this area there are many places where there was little or no damage. Reports from Cornwall indicate that only slight injury was evident in that county and not very much in Devon and Somerset. The effect of the frost only became really obvious when Wiltshire or Gloucestershire was entered; nevertheless there were several places, in Devon particularly, where damage was quite severe, these being frosty localities lying in the valleys radiating from Dartmoor, Exmoor and, in Cornwall, Bodmin Moor. This damage was not surprising for, despite the general escape of this area from really low temperatures, quite severe frosts were registered in parts of Devon; also this was one of the early areas as regards the development of the trees. The comparative absence of letters reporting damage from the southern half of Hampshire has already been commented on, the same applies to the coastal strip of west Sussex.

Section (ii), South Wales, Midlands and South-east England.—This section undoubtedly covers the area where most severe damage was done by the frosts. The large number of records from the counties south and west of London is very striking and is due perhaps to the frequency in them of woods of broadleaved species. Except in the central Midlands the places with very slight or no damage are few and far between. Where they do occur they are mostly on hilltops, for example, on the Downs, the Chilterns, the Cotswolds, and the south Wales mountains. Most of the markings in the central Midlands rest on the evidence of a single journey and if more reports had been received it is almost certain that some of them would have indicated considerable damage. Nevertheless it seems clear that Huntingdonshire, north Northamptonshire, Leicestershire, and Warwickshire were not affected so much as the rest of the section under consideration. In East Anglia the presence of severe damage near the coast is interesting; in one case quite severe injury to trees was reported actually on the sea cliffs. This is an indication of the severe frosts which were experienced in East Anglia, for, in comparison with most of the other areas in this section, it was backward in the development of the vegetation. Perhaps the most striking area is south Wales and the Forest of Dean, where, in proportion to the number of reports received, the number of places where severe injury occurred is very high; it was here and in East Anglia that some of the most severe damage to young coniferous plantations was done.

Section (iii), North Wales and North Midlands.—Information for this section is very incomplete. North Wales escaped fairly lightly, as would be expected of an area that was not subject to particularly low temperatures and was rather backward at the time of the frost. Here, as in all hilly districts, frost hollows and frosty valleys occur, and account for the blacker markings on the map. In the north to in the central Midlands most of the indications of lack of damage were based on a single journey, and wider exploration would undoubtedly have yielded more places where slight, moderate or even severe damage occurred. Nevertheless large areas in this part of the country undoubtedly did escape damage from the frost.

Section (iv), North-east England and South-east Scotland.—This section experienced very low temperatures generally and it is, therefore, surprising to find so few places showing severe damage. The frosts here were not quite so severe as those in the southern half of England, and the vegetation, particularly in the north-east was definitely more backward. These two factors combined are no doubt responsible for the comparative mitigation of damage. So far as can be judged from the inadequate distribution of points on the map, moderate damage was common, and a good many reports of serious injury to young conifers were received.

Section (v), Middle and South-west Scotland.—This was an area with a very irregular distribution of severity of damage. In the Lowlands and along the east coast damage was fairly general, if not particularly severe. On the west coast it was quite often severe and very often moderate. There is no doubt that the influence of water was much more important here than on the east coast. Areas immediately adjacent to the sea or the larger sea lochs were seldom much damaged; but in the neighbouring hills there were many valleys quite near the sea where very severe frost was experienced. These wide differences were noticeable in the temperatures recorded, but were still more striking in the severity of damage. For instance on the shores of Loch Fyne practically no damage could be seen, but on passing over a low col to the head of Glen Eck damage was at once apparent, and from there down the valley towards Dunoon an enormous amount of injury had been done to the lower lying plantations. As regards the central Highlands information is lacking both on temperatures and on the state of the vegetation at the time of the frost. So far as the temperature records extend, and they are mostly from the edge of this area, they appear to indicate that it suffered quite severe frosts. From two or three reports, however, there is definite indication that the vegetation was backward, and this is supported by the average floral isophenes (*see* Map 1, page 7). There is no doubt that many places escaped severe damage and without more accurate knowledge to the contrary, this must be attributed to the backwardness of the trees.

Section (*vi*), *North-east Scotland.*—In the western end of this area, *i.e.*, the part around Inverness, the vegetation was noticeably backward, and the degree of frost very slight; this was perhaps the most striking area in the country as regards absence of damage. Farther east where the frosts were rather more severe and the trees more advanced there was considerably more damage.

Section (*vii*), *North Scotland.*—As regards the northern Highlands data on damage, temperature and development of the vegetation are very incomplete. It is interesting to note that quite considerable damage occurred at Borgie Forest, near the north coast, so that even if it cannot be said with certainty that damage extended from Land's End to John O'Groats, it did at least do so from Cornwall to Sutherland. Trees in Orkney are hard to find, and where they do occur wind damage would soon mask frost injury, except in the most sheltered situations. In such places no trace of frost damage could be found, as indeed would be expected, since the grass minimum was only 29°F. Unfortunately no records are available for Shetland.

General.—Taking the country as a whole there seems no doubt that the areas most severely affected were the south of England (excepting the south-west and part of the south coast), East Anglia and the southern half of Wales. More important is the fact that the frosts caused considerable damage in so many places, so widely distributed. It is fortunate that so severe a period of frost seldom is so widespread.

STAGE OF DEVELOPMENT OF TREES AT THE TIME OF THE FROSTS.

The stage of development of the vegetation at the time of the frosts may now be considered. Ideally this should be done separately for each species of tree, but the information available is not sufficient. Moreover in dealing with general estimates of severity of damage, it is necessary to deal also with general estimates of the state of the vegetation, even though there is obvious difficulty in combining information on early and late flushing species. When an early district is mentioned below it indicates a locality where the bulk of the late flushing trees, such as ash and certain conifers, had broken their buds by the middle of May; a district referred to as late, is one where some, though not all, of the trees that are normally neither early nor late flushing, had broken their buds at the time of the frost. Really early flushing trees, such as larch or the Balsam poplars, had almost certainly flushed, in nearly all parts of the British Isles, well before the mid-May frosts.

Information was received from all the State forests on the condition of the trees at the time of the frost. This was collected separately for broadleaved and coniferous trees, but apart from a tendency for the broadleaved trees to be more backward little difference was noted. Information was also collected on the state of development of bracken, because this is probably the most widely distributed plant in forest areas. It was found, however, that the states of development of bracken and of trees could not be correlated. With both broadleaved trees and conifers the earliest districts were included in the country lying south of a line from the Thames to the Severn estuaries, south Wales, and western Scotland, particularly the southern end of the Great Glen. Particularly late districts were north Wales, East Anglia, north-east England, and the area round the Moray Firth. The central Highlands were probably also late, but the records are insufficient. Estimates of the state of development of trees being based solely on reports from State forests, the distribution of the areas was somewhat irregular and the outline of early and late areas given above must be regarded as approximate. Within any of the areas mentioned there must also, owing to variations in topography and local climate, be smaller areas that are earlier or later than the general average. Nevertheless it is clear that the general difference between east and west is more striking than that between north and south, and that within a general conception that south and west are early and east and north late there are exceptions, of which north Wales is perhaps the most striking.

DAMAGE TO TREES AND SHRUBS.

The information on which the estimates of severity are based was taken from the three sources mentioned previously, namely reports from the State forests, letters from readers of " *The Times* " and personal observations. Information was also taken from two papers published on damage by the frosts at Kew by Dallimore[11], and at Wisley by Mulligan[27], and from a report prepared by Dallimore on damage in the pinetum at Bedgebury in Kent. All are referred to below as " reports ", and each report deals with a separate area. The size of the area covered by a report may vary from a small garden to several square miles, and the number of trees of any one species from one to over a million.

Where it has been possible to base the estimate of damage on six or more reports no mention is usually made of the number concerned; but if it is based on less than six, the number is put in brackets, together with the letter "r", *e.g.*, (1r), (2r). It must be understood that the estimates based on a very small number of reports are of practically no value for comparative purposes, in so far as degree of susceptibility to damage is concerned. Reports of lack of injury are only given when they refer to areas where several other species were damaged. Where any comparison based on one or two records is made between two species, there is reason to believe that the trees were growing under similar conditions, in the same area. The percentage figures for the degree of damage used in the summaries are based in each case on twenty or more reports.

In describing the amount of damage suffered by the different trees and shrubs the following terms are used :—

Terms.	*Conifers.*	*Broadleaved Species.*
" Very severe " or " very serious."	Trees dead or severely cut back.	Same as for conifers but not used in the case of damaged leading shoots.
" Severe " or " serious "	Leading shoots damaged.	Most of the young shoots killed.
" Moderate " ..	Most of the shoots damaged but the leaders escaped.	About 50 per cent. of the shoots injured.
" Slight " ..	Less damage than the above; occasional injury to young shoots and needles.	Less damage than above: occasional injury to young shoots, leaves or buds.

It has not always been possible to follow these definitions precisely owing to shortcomings in some of the reports, nevertheless in spite of this it has been possible to obtain a useful indication of the frost-susceptibility of the various trees and shrubs.

The particulars given in the tables are based on detailed reports —in most cases from 500 trees.

As the headings to the columns in the tables are necessarily brief a fuller description of each is given below :—

Heading.	Description.
" Little or no damage " . .	New leaders untouched, little or no damage to side shoots.
" Only side shoots damaged "	New leaders untouched, severe damage to side shoots.
" Leaders damaged " . .	New leaders killed.
" Some older wood damaged."	Older shoots as well as new shoots damaged.
" Cut to the base " . .	Plants killed to ground level but producing new shoots from the base.
" Dead "	Plants dead.

As each planting season extends from November to the end of March it should be explained that where reference is made to the ages of trees these are taken as dating from the later portion of the planting season. For example a tree planted between 1st November, 1934 and 31st March, 1935, is referred to as having been planted in 1935. The year or years in the nursery previous to planting are not included in the age.

With regard to botanical names it has been considered better to adopt those of well-known works, rather than give the authority for each. For the conifers Dallimore and Jackson's " Handbook of the Coniferae "[12] was used, and for the broadleaved trees Bean's " Trees and Shrubs hardy in the British Isles "[5]. Certain minor departures from the names given in these publications are noted in the text; *Cupressus* has been divided into two genera *Cupressus* and *Chamaecyparis*, and *Tsuga heterophylla* has been used instead of the now less familiar *T. albertiana*.

Conifers.

Abies grandis.—A good deal of damage was done to this species both in plantations and nurseries. Most of the reports of severe damage refer to small trees. One case is known, however, where a tree over 80 ft. high had all the young shoots browned, and other cases where the damage extended to a height of 60 ft. In most of the cases of damage to small trees both the side shoots and the leaders were affected; there was some dieback of the older shoots, and four areas reported that many plants were killed. No records of uninjured stands were received, and it is probable that where conifers were damaged at all, this would be one of the species affected.

Abies nobilis.—This species is less widely planted than *A. grandis* and most of the records came from Scotland. On the average the frost was less severe in Scotland. Possibly for this reason *A. nobilis* has yielded few records of really severe damage.

Other Species of Abies.—The rest of the genus must be dealt with briefly. Damage normally took the usual form, *i.e.*, the loss of the current year's shoot, and in severely injured trees, part of the older wood was killed as well. Badly damaged trees had considerable difficulty in making fresh growth, being apparently not so well provided with dormant buds as most of those in other coniferous genera. Severe injury was suffered by the following species: *A. balsamea* (1r), *A. bracteata* (1r), *A. cephalonica* (2r), in one case it was only moderately damaged; *A. cilicica* (1r), *A. faxoniana* (1r), *A. forrestii* (2r), *A. fraseri* (1r), *A. lasiocarpa* (2r) —in one case it was undamaged; *A. nephrolepis* (3r), in one case it was only slightly damaged; *A. numidica* (1r), *A. orientalis* (1r), *A. pectinata* (4r), in one case it was only slightly damaged; *A. pindrow* (2r), in one case it was only slightly damaged; *A. recurvata*, *A. sachalinensis*, *A. veitchii* and *A. webbiana*. Very variable damage ranging from severe to none on closely adjacent trees was reported on *A. brachyphylla*, *A. koreana* and *A. mariesii* (1r in each case) and *A. firma* (2r). Slight damage was reported on *A. concolor*, *A. lowiana*, *A. nordmanniana* (1r in each case), and *A. pinsapo* (3r), in one case it was undamaged. Finally, complete lack of damage was recorded on *A. amabilis*, *A. magnifica* and *A. religiosa* (1r in each case). It is probable that some of the *Abies* species, like so many other conifers, have early and late flushing individuals, which would account for the very variable damage on adjacent trees.

Araucaria imbricata (1r) was undamaged.

Cedrus.—The cedars do not seem to have been much damaged but it is probable that most of the reports refer to old trees. Severe damage to *C. deodara* was, however, quite frequently reported. *C. atlantica glauca* (1r) was reported undamaged, *C. atlantica* (4r) undamaged to slightly damaged, and *C. libani* (2r) undamaged and slightly damaged. *C. atlantica fastigiata* (1r) and *C. brevifolia* (1r) were slightly damaged.

Chamaecyparis.—Damage on *C. lawsoniana* was very variable, but often severe. It was particularly striking because in many cases all the foliage was affected. In a conifer of this type there is less loss of leaders, and less difficulty in replacing a lost leader, than in the more geometrical trees like spruce or larch. For this reason, though the damage may appear very striking, it has not usually proved so devastating. There was very considerable difference between the varieties of *C. lawsoniana*, but in a really frosty situation none escaped entirely, and in a less frosty place none was damaged, so that no attempt will be made to detail them here. Suffice it to say that in the frosty situation "Triomphe de Boskoop" was the least affected. *C. nootkatensis* (3r), which has been recommended for planting in frosty situations, escaped lightly as compared with *C. lawsoniana*; it was more damaged than *Cupressus macrocarpa* on the same site, but would be much more winter-hardy than that species. *C. thyoides* (1r) escaped damage entirely in a hollow where the temperature is known to have fallen to 15° F., and where most other cypresses except *C. macrocarpa* were damaged. It may, therefore, be of use for shelter planting in low-lying frosty places.

Cryptomeria japonica (3r) was reported with damage varying from severe to very slight. In one of the cases of severe damage rapid recovery was made. *C. japonica elegans* (1r) and *C. japonica elegans nana* (1r) were moderately damaged.

Cunninghamia sinensis (1r) was moderately damaged.

Cupressus.—The cypresses as a whole escaped with very slight injury. *C. macrocarpa,* generally regarded as rather tender, escaped damage almost entirely. The difference between this tree and the supposedly much hardier *Chamaecyparis lawsoniana* appears at first rather surprising, but the apparent contradiction rests on a confusion between winter- and spring-hardiness. *C. lawsoniana* is winter-hardy, whereas *C. macrocarpa* is not, so that in a winter such as that of 1928–29, *C. macrocarpa,* being severely damaged, gets the reputation of being a tender tree, whereas this stricture should apply to the winter only. During the early spring the temperature at which damage is possible rises much faster for *C. lawsoniana* than for *C. macrocarpa,* by May their positions are reversed, and *C. lawsoniana* is the more frost-tender.

Cupressus arizonica (1r), *C. goveniana* (1r), *C. lusitanica* (1r), *C. macnabiana* (1r), *C. torulosa* (1r) *and C. X. leylandi* (1r) were undamaged. *C. sempervirens* (2r) was undamaged and slightly damaged and *C. macrocarpa lutea* (1r) slightly damaged. Moderate damage was done to *C. duclouxiana* (1r) and *C. macrocarpa lambertiana* (1r).

Ginkgo biloba was quite frequently reported with severe damage to the young shoots.

Juniperus.—Junipers were very little damaged. Moderate damage was reported to *J. coxii* (1r). *J. communis suecica* (2r), *J. communis nana* (1r), *J. sabina* (1r), *J. sabina tamariscifolia* (1r), *J. squamata fargesii* (1r) and *J. virginiana* (1r) were undamaged.

Keteleeria davidiana (1r) suffered from severe damage to the young shoots.

Larix europaea.—Though many reports of severe damage to European larch were received this was not one of the conifers most severely affected by the frost. The worst damage reported was 70 per cent. killed among unsheltered one-year-old seedlings in a nursery. On the other hand in a number of areas where damage had been done to other trees there was a total lack of injury to this species. As was usually the case with conifers, damage to old trees was negligible. Loss of the leading shoot was not reported on trees more than 10 years planted, but may have occurred on older trees in a few areas, as it did in the case of Japanese larch. In most cases European larch showed very good powers of recovery from frost damage and lost leaders were usually quickly replaced. Detailed counts of damage were made in a number of forest areas and a typical selection of these is set out in the following table :—

TABLE IX.

European Larch.

Year of Planting.	Percentage of Trees in Damage Classes.						Height (feet).
	Little or no Damage.	Only side Shoots damaged.	Leaders damaged.	Some older Wood damaged.	Cut to the Base.	Dead.	
1920	40	55	5	—	—	—	8–15
1927	34	20	44	2	—	—	4–9
1927	57	25	—	18	—	—	4–7
1930	87	7	6	—	—	—	3½–5
1932	67	22	1	5	—	5	1–4
1932	—	35	—	33	4	28	¾–1

It will be seen from this that the bulk of the damage was usually confined to the side shoots. For this species comparative records of damage at the three forest phenological stations are given in Table X.

TABLE X.

European Larch.

Station.	Grass Minimum.	Unscreened Minimum at 1 ft.	Screen Minimum.	Percentage in Damage Classes.		
				None or little.	Side Shoots only.	Leaders.
	° F.	° F.	° F.			
Benmore, Argyll ..	20	22	28	100	—	—
Lynford, Norfolk ..	17	18	23	49	31	20
Nagshead, Forest of Dean	9	18	24	—	—	100

It is curious that the very low temperature recorded at Nagshead, while damaging all the leaders, should have failed to kill any of the plants.

In three areas it was possible to make some comparison between European larch of different seed origins. At Lael Forest, in Ross-shire, larch from a large number of Scottish seed sources have been planted with one lot of Swiss and two reputed to be of Silesian seed origin. On the whole the Scottish lots escaped very lightly, but in two lots many of the trees were quite badly damaged. The Swiss lot also escaped with only slight damage, but both the supposed Silesian plots were damaged, and some plants in them, badly. In a similar set of plots at Clashindarroch Forest, Aberdeenshire, detailed counts were made and the lots of Scottish seed origin compared very favourably on the whole with the Swiss and Silesian plants. In Table XI the two most severely damaged Scottish races, and an average figure for all the Scottish races are given for comparison with the Silesian and Swiss lots. All the trees were planted in 1931.

TABLE XI.

European Larch.

—	Percentage of Trees in Damage Classes.						Height (feet).
	Little or no Damage.	Only side Shoots damaged.	Leaders damaged.	Some older Wood damaged.	Cut to the Base.	Dead.	
Scottish (average)	30	24	18	24	1	3	1–2
Scottish (Barcaldine)	12	8	16	44	16	4	1½–2
Scottish (Taymouth)	10	28	17	33	—	12	1½–2
Swiss	4	10	6	54	—	26	1½
Silesian (*a*) ..	4	8	8	42	2	36	1–1½
Silesian (*b*) ..	4	4	8	62	4	18	1

In this case both the Silesian and the Swiss lots show up very badly even as compared with the worst of the Scottish lots. These data are supported by those obtained from the forest plots at Bedgebury in Kent. Here out of five plots, that of Silesian seed origin was the worst affected, being severely damaged. Next to this in order of damage came a plot of Swiss origin, which suffered moderate damage, and the least affected were three plots of Scottish origin, two of which were slightly and one moderately damaged. These differences are not so striking as, for instance, that between early and late flushing Norway spruce, or as that between European larch and Sitka spruce. It cannot be said that larch of Scottish origin is frost-hardy, nor that Silesian larch is, in comparison, particularly frost-susceptible.

Larix leptolepis.—The reports received suggest that Japanese larch was rather more affected by the frosts than European larch. The difference is slight, however, and in a large number of instances reports from the forests stated that there was no difference in amount of damage between the two species. As with European larch in a large number of areas where damage had been done to other trees there was an absence of injury to Japanese larch. No reports of injury to old trees were received, but the lower branches of older trees must have been to some extent damaged in colder sites. In one place damage to the leaders was seen on trees 30–35 ft. high. Japanese larch has two advantages over European larch as regards frost. Firstly it is of more rapid growth when young, and therefore its leaders are likely at an earlier age to get above the cold air near the ground. This advantage however does not seem to have availed it much. The second, and more important advantage, lies in its greater powers of recovery. European larch, if not frosted year after year, usually recovers from frost, but Japanese larch by the extreme vigour of its growth will often more than make good its annual losses by frost. Often in situations where European larch would gradually go into check and die Japanese larch eventually grows sufficiently tall to escape all but the most exceptional frosts. Neither species has the same power as Norway spruce of recovery from continued frosting and will die if heavily frosted year after year. It is often very noticeable that after a single frosting, Japanese larch recovers much more quickly than European larch so that at the end of two or three months signs of damage have almost disappeared from the Japanese larch but are still quite apparent on the European. Detailed counts of damage were made in a few forest areas as shown in the table below.

TABLE XII.

Japanese Larch.

Year of Planting.	Percentage of Trees in Damage Classes.						Height (feet).
	Little or no Damage.	Only side Shoots damaged.	Leaders damaged.	Some older Wood damaged.	Cut to the Base.	Dead.	
1930	75	25	—	—	—	—	5
1931	29	14	21	—	10	26	2–3½
1932	41	35	4	15	2	3	1–4

Larix eurolepis.—Unfortunately the number of reports for hybrid larch is comparatively small and most of them are from Scotland. So far as the records go it seems often to have escaped lightly. Rapid growth in youth and early escape from frost danger, are more striking with this species than with Japanese larch. In the forest plots at Bedgebury in Kent, one plot of hybrid larch escaped any serious damage almost entirely because of its superior height. Another younger plot was moderately damaged and was in no way more resistant than European or Japanese larch.

Detailed counts of damage were made in a few forest areas and are set out in Table XIII.

TABLE XIII.

Hybrid Larch.

Year of Planting.	Percentage of Trees in Damage Classes.						Height (feet).
	Little or no Damage.	Only side Shoots damaged.	Leaders damaged.	Some older Wood damaged.	Cut to the Base.	Dead.	
1931	52	20	3	20	—	5	1½
1932	64	28	6	2	—	—	1–2
1933	90	4	2	4	—	—	1
1933	67	—	33	—	—	—	1

Larix occidentalis.—The following detailed count was made of damage on this species :—

TABLE XIV.

Larix occidentalis.

Year of Planting.	Percentage of Trees in Damage Classes.						Height (feet).
	Little or no Damage.	Only side Shoots damaged.	Leaders damaged.	Some older Wood damaged.	Cut to the Base.	Dead.	
1931	17	25	25	33	—	—	2–2½

Only one other report was received, it recorded slight damage.

Other Species of Larix.—Very little information was collected on the rest of the genus. *L. potanini* (2r), was reported moderately damaged. In the pinetum at Bedgebury *L. pendula* was uninjured, whereas all the other larch species showed some degree of damage.

Picea sitchensis.—Sitka spruce suffered worst of the more important forest conifers. There were many records of very severe damage, *i.e.*, many plants killed or with a good deal of the old wood dead. The worst record was one of 75 per cent. killed in a plantation formed in 1934. Losses of 25 per cent. killed were reported among trees planted from 1931 to 1934, and among one-year-old seedlings in a nursery. It should not be supposed, however, that this species was everywhere severely damaged. In a number of places it was not sufficiently advanced to receive much damage, and in others it escaped owing to a fortunate choice of situation. Very few cases of damage to old trees were reported, though the lower branches may have been affected in really frosty places. One record of damage up to 50 feet on mature trees was received, but loss of the leading shoot was not reported on trees more than 15 years planted. The damage, which was normally of the types usually occurring on conifers, is well illustrated by Plate I, figs. 1 and 2, and Plate IV, fig. 1 The estimation of the amount suffered by this species and by *Picea excelsa* was somewhat complicated by defoliation by the green spruce aphis, *Neomyzaphis abietina.* Loss of the previous year's needles due to this cause may in some instances have led to an over-estimation of the amount of damage due to frost. In one case, however, it seems fairly certain that the old needles on Sitka spruce in a young plantation were killed by the May frosts, whereas the bulk of the buds was unhurt. These buds were closed, or only just opening at the time of the frost; but then even it is unusual to get damage of this type so late in the season. The considerable powers of recovery possessed by this species are well illustrated by Plate I, fig. 2, but even more striking is its capability of withstanding repeated frostings year after year. Under these circumstances if forms a dwarf rounded bush, Plate V, fig. 1. A case is known where, owing to repeated frost damage, a Sitka spruce 21 years old had not yet reached a height of one foot. This power to survive repeated prunings by frost does not always enable the trees to grow to serviceable size, and cannot be regarded as much of an advantage from a silvicultural point of view. Sitka spruce is remarkably even in its time of flushing, so that in any given place most of the trees flush within a comparatively limited period, there is therefore no chance with this species, as there is with Norway spruce, of selecting a late flushing race for use in frosty situations. On unfavourable sites, however, the spruces are very liable to become checked, making practically no growth for a number of years after planting. In this condition they tend to flush late, and in places it is probable that this saved them from severe damage.

Detailed counts of damage were made in a large number of forest areas and a typical selection of these is set out in Table XV.

TABLE XV.

Sitka Spruce.

Year of Planting.	Percentage of Trees in Damage Classes.						Height (feet).
	Little or no Damage.	Only side Shoots damaged.	Leaders damaged.	Some older Wood damaged.	Cut to the Base.	Dead.	
1924	45	25	16	6	4	4	5
1925	35	54	11	—	—	—	3–4
1926	1	21	17	28	32	1	5–8
1929	—	21	60	17	1	1	5–5½
1930	18	56	18	8	—	—	3–5
1931	—	2	2	94	4	—	1½–4½
1931	9	10	80	1	—	—	5
1931	37	37	32	2	1	1	2–6
1931	53	—	—	24	4	19	1
1931	81	3	16	—	—	—	2–2½
1932	20	60	20	—	—	—	1–3
1932	35	9	2	27	16	11	1½

It will be seen from this table that in many cases quite a high percentage of leaders was damaged. At all three forest phenological stations every plant of this species suffered, but the damage was most severe at Nagshead, in the Forest of Dean, where every leader was killed. In the forest plots at Bedgebury, in Kent, where plants of different seed origins have been planted side by side there was very little difference between the various lots, though it is possible that those of Californian seed origin were injured rather more than those from Alaska and from Queen Charlotte Islands. Under experimental conditions it has not proved possible to substantiate this difference, and at Bedgebury any difference was not sufficient to render the use of Californian seed undesirable on account of increased risk.

Picea excelsa.—Norway spruce differs from Sitka spruce in possessing well-defined, early and late flushing races. Usually in any normal lot of plants these occur mixed, with a tendency for the early flushing to outnumber the late flushing trees. This character of relative time of flushing is practically constant from year to year. The early flushing trees are quite as susceptible to frost as Sitka spruce, but the late ones are much more resistant. In really frosty places the early flushing plants tend to get killed out, and a pure stand of the late flushing race remains. In considering frosts of one year only, the mixture of late flushing trees in any stand of this species merely has the effect of lowering the percentage of damaged, or at any rate of severely damaged, trees. The difference in susceptibility is not confined merely to the time of flushing; before either race has flushed the late variety is markedly the more hardy. On the other hand once it has flushed it is not appreciably more resistant than the early variety. The mixture of these more frost-resistant trees in any plantation of Norway spruce caused this species to be rather less damaged by frost than Sitka spruce. It must be admitted that this difference was often very slight, and seldom very marked. There were, however, with Norway spruce no cases of devastating damage as were reported for Sitka spruce, the highest death-rate known being 25 per cent. among one-year-old seedlings. Only one report of damage to old trees was received, though injury must have occurred elsewhere to some extent. In this one case quite large trees standing in a frost valley lost all their young shoots, so far as could be seen, to the very top. As with Sitka spruce loss of the leading shoot was not reported on trees more than 15 years planted. In estimating the amount of damage to this species there was the same difficulty with attack by green spruce aphis. The types of damage mentioned under Sitka spruce apply also, though no case of defoliation of the old needles without damage to the buds was recorded. Norway spruce has, like Sitka spruce, the habit of checked growth after planting on poor sites, and in the same way this may have affected the amount of damage in certain cases.

TABLE XVI.

Norway Spruce.

Year of Planting.	Percentage of Trees in Damage Classes.						Height (feet).
	Little or no Damage.	Only side Shoots damaged.	Leaders damaged.	Some older Wood damaged.	Cut to the Base.	Dead.	
1920	48	50	2	—	—	—	8–15
1922	17	40	33	10	—	—	2½
1925–26	46	21	18	10	4	1	2–7½
1929	80	17	2	1	—	—	2–5½
1930	10	5	69	13	3	—	4
1930	62	18	20	—	—	—	3–3½
1930	63	30	7	—	—	—	1–2
1930	94	4	2	—	—	—	1½–2
1931	34	27	20	15	—	4	1½–3½
1931	—	17	83	—	—	—	1½–2
1933	15	45	40	—	—	—	1–1½
1934	24	2	45	22	—	7	½–1

Detailed counts of damage were made in a large number of forest areas and a typical selection is set out in Table XVI. It will be seen from this that there was usually less damage to the old wood in Norway, than in Sitka spruce.

In the forest plots at Bedgebury where Norway spruce of three different seed origins has been planted side by side there was little difference between the various lots, though the plants of Tyrolese seed origin were rather more damaged than those whose seed came from the Harz Mountains and Invergarry in Scotland. The differences between these plots were quite outweighed, however, by the differences in the late and early flushing plants within them. At Horselawn, in the Forest of Dean, an experimental area has been planted with early and late flushing Norway spruce. Unfortunately in this case the sorting into the two races has not proved very satisfactory and there is a considerable number of early flushing plants among the late, and vice versa. On 15th May (the most serious frost in this locality was on the 17th), the state of the trees was as under :—

	Early Plots. (per cent.)	*Late Plots.* (per cent.)
Buds flushed	29	8
Buds swollen	61	49
Buds closed	10	43
Plants badly frosted ..	5	0

In both cases these figures are based on more than 500 trees. On 22nd May after the worst frosts were over the percentage of badly frosted trees in the early plots had increased to 29 per cent., whereas in the late plots it was only 8 per cent. It is quite certain that, if the races had been more pure in the two sets of plots, the differences would have been more striking. The lowest temperature recorded in the immediate neighbourhood of these trees was 10° F., and it may at first sight seem surprising that so little damage was done. The trees were very backward, however, owing to the cold situation.

Picea omorika.—This species is not very commonly planted, and only seven records were received. Four of these reported total absence of damage, two slight damage, and one moderate damage, though in the last case the species compared favourably with Norway spruce. At Bedgebury, where Norway and Sitka spruce were severely damaged, the freedom from injury of *P. omorika* was very striking; only a few trees suffered injury, and those not seriously. It would seem to have definite possibilities as a forest tree for frosty localities.

Other Species of Picea.—Certain species notably *P. asperata* (2r) and *P. likiangensis* (1r) have early and late flushing individuals, and may, like Norway spruce, have definite races. Damage varied from slight to severe on different trees. More generally severe damage was suffered by *P. albertiana* (1r), *P. glehni* (1r), *P. jezoensis* (4r), *P. morinda* (1r), *P. morindoides* (1r), *P. morrisonicola* (1r) and *P. wilsoni* (1r). *P. orientalis* (2r) was undamaged in one case, but severely damaged in the other. Moderate damage was reported on P. *alba* (2r)—slight damage in one case, *P. engelmanni* (1r) and *P. nigra* (1r). Slight damage was recorded on *P. bicolor* (1r), *P. brachytyla* (1r), *P. koyamai* (1r), *P. maximowiczii* (1r) and *P. pungens* (3r), though in the case of the last, two records were of no damage. *P. breweriana* (1r), *P. polita* (1r) and *P. rubra* (1r) escaped damage.

Pinus sylvestris.—Scots pine is rightly regarded as a frost-resistant tree. Its behaviour in 1935 did not belie its reputation. Most of the reports received recorded absence of damage, and omission of Scots pine from many reports despite the fact that it is so commonly planted, suggests that the absence of damage was considered too obvious to be worth recording. This hardiness was not in any way associated with lateness of flushing, for in most areas the pines were in the " candle " stage, the shoots having started to elongate, but not the needles. Scots pine is fundamentally resistant to late frosts, regardless of its state of development. Detailed counts were made in a few areas and are set out in Table XVII.

TABLE XVII.

Scots Pine.

Year of Planting.	Percentage of Trees in Damage Classes.						Height (feet).
	Little or no Damage.	Only side Shoots damaged.	Leaders damaged.	Some older Wood damaged.	Cut to the Base.	Dead.	
1928	62	35	3	—	—	—	1½
1928	85	15	—	—	—	—	3
1928	95	5	—	—	—	—	4
1928	97	3	—	—	—	—	1–4

It will be seen that where damage was recorded it was usually very slight. The two places where moderate damage was found were both particularly frosty areas. Damage was almost entirely confined to the side shoots. In one area a number of pines died in the autumn and were found to have been girdled at the base almost certainly by the May frosts.

Pinus laricio.—Corsican pine was undoubtedly more injured than Scots, though the damage was not on the same scale as that suffered by the really susceptible coniferous species. In one lot of trees planted in 1929 and 1930 a death-rate of 10 per cent. occurred. Several cases of damage in nurseries were reported, one of these concerned 1935 seedlings, nearly all being killed. One detailed assessment of damage in this species was received, see Table XVIII.

TABLE XVIII.
Corsican Pine.

Year of Planting.	Percentage of Trees in Damage Classes.						Height (feet).
	Little or no Damage.	Only side Shoots damaged.	Leaders damaged.	Some older Wood damaged.	Cut to the Base.	Dead.	
1929	47	13	8	16	11	5	1–4½

Damage occurred not only to young side shoots but also to leaders and to the old needles and in some cases extended to the old wood. In a good many areas Scots pine, growing among or beside damaged Corsican pine, were uninjured. The count given above cannot be regarded as typical, most of the reports recording complete freedom from damage.

P. laricio nigricans (5r) was reported undamaged and slightly damaged.

Pinus contorta.—Contorta pine suffered to about the same extent as Corsican pine; the maximum death-rate was the same for a plantation of the same age. In one nursery there was a 50 per cent. loss among one-year-old seedlings. In a number of cases damage was entirely confined to the old needles which turned brown and fell off, otherwise it took very much the form described under Corsican pine.

Detailed counts were made in a few areas and a typical selection of these is set out in Table XIX.

TABLE XIX.
Contorta Pine.

Year of Planting.	Percentage of Trees in Damage Classes.						Height (feet).
	Little or no Damage.	Only side Shoots damaged.	Leaders damaged.	Some older Wood damaged.	Cut to the Base.	Dead.	
1928	30	70	—	—	—	—	3½
1928	50	50	—	—	—	—	3
1928	55	45	—	—	—	—	3½
?	85	12	3	—	—	—	1
1931	90	10	—	—	—	—	3½

It will be seen that damage, though frequent, was seldom more than moderate.

Other Species of Pinus.—Severe damage was reported on three Asiatic species *P. mongolica* (1r), *P. parviflora* (1r) and P. 17365 of Forrest; it extended to the old needles in the last two of these. Slight damage was recorded on *P. monticola* (1r) and *P. pumila* (1r). *P. excelsa* (2r) was reported undamaged and moderately damaged. Complete absence of injury to shoots and leaves was reported for *P. strobus* (3r), but in one case the flowers were destroyed. *P. cembra* (2r), *P. montana* (2r), *P. pinaster* (3r), and *P. ponderosa* (3r) were undamaged, and there is little doubt that most other species grown in this country might have been reported on similarly.

Pseudotsuga douglasii.—In the amount of damage done Douglas fir stands between the larches and the spruces. Several records of very severe damage were received, notably 70 per cent. killed in an area planted in 1934, and 43 per cent. killed in one planted in 1935. Less devastating, but nevertheless very serious, were losses of 71 per cent, and 68 per cent. of the leaders in two plantations formed in 1932. Many areas reported complete absence of damage. The comparative lack of injury in Scotland was very noticeable; whether this was due to a fortunate choice of planting sites, or to the fact that the plants were backward is difficult to ascertain. The state of development of the trees was probably the cause, for good soil and shelter from wind are usually the controlling factors in the choice of sites for Douglas fir, and these conditions are often found in very frosty localities. More reports of damage to large trees were received than in the case of any other conifer; but this may be due to the frequent choice of Douglas fir as an ornamental tree. Where damage occurred it did not extend to the full height of mature trees; the oldest trees which were reported to have lost the leading shoots were planted in 1921. Douglas fir shows a very wide variation in its time of flushing, like Norway spruce, though there is perhaps a larger number of intermediates between the early and late flushing trees. The difference between the two types is clearly shown in Plate II, fig. 1; the photograph was taken a few days after the frost, and practically no harm has been done to the tree on the left, which has not yet opened its buds. Damage to swollen, but unopened, buds was recorded in a number of cases on this species, but the injury was not so serious as in the case of fully expanded buds.

A selection of detailed counts of damage is set out in Table XX.

In the Bedgebury forest plots it is possible to compare Douglas fir of three seed origins, and to see the effect that damage had on their growth during the year. The three plots were (*a*) from the mountains of British Columbia, (*b*) from near the coast of British Columbia and (*c*) from the west of the Cascade Mountains in Oregon, U.S.A. In Table XXI are given the percentage badly frosted and the percentage of the trees which suffered damage to the old wood. The trees were planted in 1931 and measurements were made in November 1935.

TABLE XX.

Douglas Fir.

Year of Planting.	Percentage of Trees in Damage Classes.						Height (feet).
	Little or no Damage.	Only side Shoots damaged.	Leaders damaged.	Some older Wood damaged.	Cut to the Base.	Dead.	
1924	28	26	32	11	3	—	6–11
1926	27	24	32	10	4	3	8–10
1926	20	15	45	20	—	—	2–12
1929	88	11	1	—	—	—	8½–11½
1931	27	1	64	4	2	2	2½–4
1934	24	9	22	29	13	3	1–2

TABLE XXI.

Douglas Fir Plots, Bedgebury.

Plot.	Total No. measured.	Badly frosted.	Trees with Damage to older Wood.			No Damage to older Wood.		
			Percentage.	Mean Ht.	Mean Shoot.	Percentage.	Mean Ht.	Mean Shoot.
		per cent.		*in.*	*in.*		*in.*	*in.*
a.	219	46	29	31·6	1·3	71	60·6	10·6
b.	216	39	24	53·75	1·0	76	103·5	17·8
c.	213	85	75	24·2	0·6	25	60·0	8·5

It will be seen that in general the amount of damage was inversely proportional to the height of the trees, and there is no doubt that the comparative escape of the British Columbia coast plants (Plot *b*) was in part due to many of the leaders being above the cold air. The difference between the other two plots, however, is due to the origin of the seed. On the evidence of this one example no broad conclusions can be drawn, other than that further investigation of different seed origins, and of early and late flushing races would be useful.

Other Species of Pseudotsuga.—Only one report of damage to *P. glauca* was received; this was of a large tree, with the shoots damaged for two thirds of its height. It was standing beside a large green Douglas fir which was undamaged. The distinction between the several species and varieties of Douglas fir was not always observed, however.

Sciadopitys verticillata (1r) was undamaged.

Sequoia sempervirens (3r) was reported with damage varying from slight to severe, and *S. gigantea* (1r) undamaged.

Taiwania cryptomerioides (1r) was undamaged.

Taxodium distichum (3r) varied from undamaged to moderately damaged.

Taxus baccata would appear from the eighteen records to have been frequently, but seldom severely, damaged; but in three cases absence of damage was reported. Damage where it occurred was confined to the young shoots. *T. cuspidata* (1r) was moderately damaged, and *T. baccata fastigiata* (3r) and *T. baccata fastigiata aurea* (1r) were undamaged.

Thuya.—This genus does not seem to have been much affected by the frost. *T. plicata* was reported severely damaged in one case, where the trees subsequently developed very striking cankers, but otherwise only slightly damaged or undamaged. *T. dolabrata* (2r) was reported undamaged and with slight damage, and *T. orientalis* (1r) undamaged.

Tsuga.—A considerable amount of damage seems to have been done to this genus. A good many reports of severe damage to *T. heterophylla* were received, though in other cases it escaped damage or was only slightly injured. One detailed count of damage in a forest area was made (Table XXII).

TABLE XXII.

Tsuga.

Percentage of Trees in Damage Classes.						Height (feet).
Little or no Damage.	Only side Shoots damaged.	Leaders damaged.	Some older Wood damaged.	Cut to the Base.	Dead.	
66	24	10	—	—	—	7–10

T. chinensis (1r), *T. diversifolia* (1r) and *T. pattoniana* (1r) were severely damaged, and *T. sieboldi* (1r) received damage varying from severe to slight.

Order of Susceptibility to Damage.

Table XXIII has been compiled to indicate the order of susceptibility of the more important conifers. It shows first the percentage of the reports which come under the different degrees of damage described on page 48. The " severity index " in the last column has been arrived at by allotting 4 points to very severe damage, 3 to severe, 2 to moderate and 1 to slight damage; the percentage in each damage class was next multiplied by the appropriate number and the resulting figures added up for each species.

TABLE XXIII.

Species.	Percentage of Reports in Damage Classes.					Total No. Reports.	Sever-ity Index.
	Very Severe.	Severe.	Mode-rate.	Slight.	None.		
Abies grandis	24	33	5	38	—	21	243
Picea sitchensis	10	41	15	22	12	333	215
Picea excelsa ..	4	38	18	30	10	261	196
Pseudotsuga douglasii	5	32	13	29	21	162	171
Larix leptolepis	3	29	19	31	18	136	168
Larix europaea	5	24	13	41	17	126	159
Pinus contorta	6	9	12	15	58	33	90
Pinus laricio ..	6	9	6	6	73	31	69
Pinus sylvestris	—	—	2	11	87	83	15

TABLE XXIV.

Species.	Number of Reports in Damage Classes.					Total Number of Reports
	Very Severe.	Severe.	Moder-ate.	Slight.	None.	
Abies nobilis	1	3	1	3	1	9
Cedrus deodara	—	1	5	1	2	9
Chamaecyparis lawsoniana	—	2	2	2	3	9
Cupressus macrocarpa ..	—	—	—	—	8	8
Larix eurolepis	—	1	2	3	3	9
Picea omorika	—	—	1	2	4	7
Taxus baccata	—	1	3	4	3	11
Thuya plicata	—	1	—	3	4	8
Tsuga heterophylla ..	1	5	1	3	3	13

The species in Table XXIII have been divided into three groups. The first contains the frost-susceptible conifers, the second the fairly hardy, and the third the really hardy, in this case Scots pine alone.

The conifers for which more than six but less than 20 records are available are set out in Table XXIV. The actual number of records in each damage class is given, not the percentage. It is of interest to compare the above assessments with the information available in previous papers on late frosts. Many scattered observations on damage by late frost have been made, particularly on the Continent. In this country a series of papers was published by Elwes[14,15,16] on late frost damage at Colesborne, but as the observations were made in some cases on a very small number of trees growing sometimes in sheltered and sometimes in very frosty places, they will not be considered further here. Of more general interest is the paper by Somerville[43] on the damage caused by the May frosts of 1894. It was based on 27 reports sent in by members of the Royal English Arboricultural Society. Roth[40], concerned with May frosts in Hungary, chiefly that of 1911, gives estimates of damage for a large number of species. Provis[36], referring to late frosts in Belgium, gives a list of relative resistance for a few species, basing his data mainly on observations made after the late frosts of 1921. Schädelin[41] gives the susceptibility for a number of species in the frosts at the end of May and beginning of June, 1918. Borgmann and Funk[6], summarising a number of

TABLE XXV.

Species.	Somerville.	Roth.	Provis.	Schädelin.	Borgmann and Funk.	Greenfield.
Abies grandis ..	—	Sev.	Sev.	—	—	—
Picea sitchensis ..	—	Sev.	—	—	Sev.	—
Picea excelsa ..	Sev.	Mod.	Mod.	Sev.	Sev.	Sev.
Pseudotsuga douglasii	Sl-N.	Mod.	—	—	Sev.	Sev.
Larix leptolepis ..	—	Mod.	—	—	Mod.	—
Larix europaea ..	Sev.	Mod.	—	—	Mod.	Sev.
Pinus contorta ..	—	Sl-N.	—	—	—	—
Pinus laricio ..	—	—	—	—	—	Sl-N.
Pinus sylvestris ..	Sl-N.	Sl-N.	Sl-N.	Sl-N.	Sl-N.	Sl-N.
Abies nobilis ..	—	Mod.	—	—	—	—
Chamaecyparis lawsoniana	—	Mod.	—	—	Sl-N.	—
Taxus baccata ..	Sev.	—	—	—	—	—
Thuya plicata ..	—	Sev.	—	—	—	—
Tsuga heterophylla	—	Sev.	—	—	—	—

papers on late frost, arrange a large number of species in order of susceptibility. Finally, a similar list is given by Greenfield[20], in a general paper on late frosts. All these papers divide the trees into three susceptibility classes which, while named differently, may be roughly described as severe, moderate, and slight-none. In Table XXV the abbreviations " Sev.", " Mod." and " Sl.-N.", indicate the estimates of susceptibility given by the various authors, for the species with which we are concerned.

In general these observations agree reasonably well with those made in this country after the frosts of May 1935. Somerville's classification of Douglas fir as a hardy tree is rather surprising, and in the recent frosts *Thuya* was not so much damaged as Roth's classification, or past experience in this country would lead one to expect.

Experiments, the results of some of which have been published[13], have been carried out in a refrigerator with some of the species with which we are here concerned. The so-called critical temperatures given in Table XXVI are the temperatures for mid-May at which half the number of plants used were damaged. Where a range of temperatures is given it indicates that the critical temperature varied in different experiments.

TABLE XXVI.

Species.	*Critical Temperature.* ° F.
Picea sitchensis	24–26
Picea excelsa (early)	26
Picea excelsa (late)	22–24
Picea omorika	23
Pseudotsuga douglasii	26
Larix leptolepis	23–26
Larix europaea	23–25
Pinus sylvestris	23
Thuya plicata	27

In general these fall as would be expected, though the high figure for *Thuya plicata* agrees rather with the observations on other late frosts, than with those for May 1935. Perhaps the most striking point in the experiments was the extremely small alteration in the critical temperature that is sufficient to make a very marked difference in the amount of damage.

On the question of relative hardiness of the conifers the tables give sufficient data without further comment. The fact that in certain genera there are particularly resistant species and in certain species, resistant late-flushing races, suggests that attention should be turned to developing and improving such hardy species and races by breeding and selection.

Broadleaved Trees and Shrubs.

Abelia schumannii (1r) growing on a wall was undamaged.

Abutilon vitifolium (2r) was undamaged.

Acacia dealbata (1r) was undamaged but it was growing on a wall.

Acanthopanax ricinifolius (1r) was severely damaged.

Acer pseudoplatanus.—The effect of the frosts on the sycamore varied. The tree has the reputation of being hardy, but a surprisingly large number of reports of severe damage was received. In its final effect on the tree damage was not usually serious except in very young trees. A large number of records referred only to the leaves, which were often scorched at the margins and there were many reports of absence of damage. The amount of damage that could occur in a young plantation is illustrated by the detailed figures given in the following table :—

Table XXVII.

Sycamore.

Year of Planting.	Percentage of Trees in Damage Classes.						Height (feet).
	Little or no Damage.	Only side Shoots damaged.	Leaders damaged.	Some older Wood damaged.	Cut to the Base.	Dead.	
1934 ..	14	—	20	31	22	13	½–1½

Under forest conditions the sycamore is not a very easy tree to establish by planting and the liability of young plants to damage by late frost increases the difficulty. For, unless the trees are making vigorous growth they do not recover if severely cut back. Many of the reports referred to large trees and on these the injury, while appearing severe soon after the frost, in only a few cases harmed the trees permanently. In many situations where oak, beech and ash were damaged this tree escaped, so that it can only be regarded as moderately frost-susceptible.

Other species of Acer.—Our native maple, *A. campestre,* proved hardier than the sycamore, for of the fourteen reports on this species, eight were of complete absence of damage, and severe injury was reported only in one case. *A. platanoides,* the Norway maple, proved even hardier, for of the six records received all were negative. *A. platanoides reitenbachii* (2r) was undamaged, but *A. platanoides schwedleri* (2r) suffered from slight and from moderate damage. The worst affected of all the maples, and one of the most severely injured of commonly planted ornamental shrubs was *A. palmatum*, the Japanese maple, and its varieties. Most of the other species were hardy, but *A. macrophyllum* (1r) was reported severely damaged and *A. ginnala* (2r) moderately damaged and undamaged. Complete absence of damage was reported on *A. circinatum* (1r), *A. dasycarpum* (2r), *A. griseum* (3r), *A. laetum rubrum* (1r), *A. negundo variegatum* (2r), *A. negundo californicum* (1r), *A. pennsylvanicum* (1r), *A. rubrum* (2r) and *A. rufinerve* (1r).

Actinidia chinensis (2r) and *A. kolomikta* (2r) were reported undamaged or only slightly damaged; in both cases they were growing on walls.

Aegle sepiaria (1r) was reported with moderate damage to the young shoots.

Aesculus hippocastanum, the horse chestnut, did not suffer so badly from the frosts as many other broadleaved trees. Nevertheless reports of severe damage to the young leaves were quite frequently received. There is a very considerable difference in stage of development between individuals of this species in the spring; but few trees can have been sufficiently backward in mid-May to have escaped damage for that reason, and it would seem that even when flushed, this is not a particularly frost-susceptible tree. A very large number of reports indicated damage to the flowers only.

Aesculus parviflora (1r) was reported severely damaged, *A. carnea* (2r) severely and slightly damaged, *A. californica* (1r) moderately damaged, and *A. indica* (2r) slightly damaged.

Ailanthus glandulosa was often severely damaged but as the tree when established has amazing powers of recovery from pruning, probably little permanent damage was done.

TABLE XXVIII.

Oregon Alder.

Year of Planting.	Percentage of Trees in Damage Classes.						Height (feet).
	Little or no Damage.	Only side Shoots damaged.	Leaders damaged.	Some older Wood damaged.	Cut to the Base.	Dead.	
1932 ..	—	—	5	28	27	40	5–6
1934 ..	4	—	—	10	20	66	—
1934 ..	—	—	—	50	—	50	—
1934 ..	52	—	—	40	—	8	—

Alnus oregona.—Oregon alder has some possibilities as a forest tree and may be particularly useful as a nurse for other more valuable species on difficult sites such as chalk downs. It also has made very good growth on deep peats and on clays, but as regards late frost, it is not a hardy tree. Several reports of extremely severe damage were received, such as 90 per cent. and 70 per cent. killed in plantations formed in 1935, and 50 per cent. killed in one-year-old seedlings in a nursery. Even more serious was the effect of frost in a difficult peat area, shown in the first line of figures in Table XXVIII.

A number of forests reported only slight damage to this species, but only two no damage, and in one the plants were sheltered.

Other Species of Alnus.—Very severe damage was reported on the grey alder, *A. incana*, notably 66 per cent. killed in nursery transplants. As compared with *A. oregona* there was a higher percentage of reports of slight or no damage. Only six reports were received referring to the common alder, *A. glutinosa*, by name, but it is certain that a number referring to *Alnus* spp. applied to this species. So far as can be judged it was not often damaged, but two reports of severe damage were received. In comparing *Alnus* with other genera it must be remembered that as a stream and bogside tree it is very often grown in situations particularly subject to frost, and seldom in places particularly frost free.

Alnus viridis (1r) was reported with damage from moderate to severe, *A. cordifolia* (4r) with damage from slight to very severe. *A. sitchensis* (1r) was moderately damaged, and *A. serrulata* (1r) undamaged.

Amelanchier canadensis (1r) and *A. laevis* (1r) were undamaged.

Aralia chinensis (probably) (2r) was moderately to severely damaged.

Arbutus unedo (1r) was undamaged. *A. menziesii* (1r) was reported with severe damage to the leaves.

Arundinaria japonica (1r) was reported with the leaves very slightly damaged.

Aucuba japonica varieties (3r) were reported only slightly damaged, with the exception of *A. japonica crassifolia* (1r) which was severely damaged.

Azara microphylla (1r) was reported with moderate damage to the young shoots.

Berberis.—Information on this genus is very incomplete. In general it was probably not much damaged. Reports of moderate damage have, however, been received for the following species, (1r) in each case :—*B. acuminata, B. bergmanniae, B. chitria, B. ferdinandi-coburgii, B. jamesiana, B. japonica bealei, B. julianae, B. pruinosa, B. replicata* and *B. sargentiana.*

Betula.—In the reports received on the birch it proved impossible to separate *B. pubescens* and *B. verrucosa*, the two species which form the original *B. alba L.* Most of the records referred to " birch ". There seems no reason to suppose that one species escaped better than the other. Birch proved one of the hardiest trees, and in areas where damage was very severe on many other trees birch was usually free from injury, or at the most very slightly injured. One case was recorded where natural seedlings of birch had been killed, and one case where quite severe damage had been done to comparatively mature plants. This was exceptional and there is no doubt that birch is a really frost-hardy tree. *B. lenta* (1r) and *B. papyrifera* (1r) were reported undamaged.

Buddleia variabilis was generally reported with the young shoots injured, the damage varied from very slight to severe. *B. globosa* (2r) was undamaged, as was *B. colvilei* (1r). Of the more newly introduced species *B. fallowiana* (1r) and *B. forrestii* (1r) were severely damaged, *B. stenostachya* (1r) moderately damaged, and *B. alternifolia* (1r) undamaged.

Buxus sempervirens was generally reported with the young shoots injured, the damage varied from very slight to very severe. The appearance of box edgings and hedges covered with dead leaves which had turned a pale cream colour was striking for some time after the frost.

Caesalpinia japonica (1r) was undamaged.

Callicarpa japonica (1r), growing on a wall, was reported with severe damage to the young shoots.

Callistemon speciosus (1r) was undamaged.

Calycanthus floridus (1r) was undamaged.

Camellia japonica (3r) had the young shoots moderately to severely damaged, whereas *C. cuspidata* (1r) was only slightly damaged.

Campsis chinensis (1r), growing on a wall, was reported with slight damage to the young shoots.

Carpenteria californica (3r) was undamaged, but it is usually planted in particularly sheltered spots.

Carpinus betulus.—Hornbeam almost rivals birch in its hardiness. Most of the records received were of absence of damage, though in three cases severe damage to the new growth on hornbeam hedges was reported. Nothing worse than slight damage was reported on large trees. In spite of the cases just mentioned, hornbeam must be regarded as a much better hedging plant than beech for really frosty places.

Carya tomentosa (1r) and unspecified spp. (1r) were reported severely, and *C. alba* (1r) moderately, damaged. Injury seems to have been confined to the leaves.

Caryopteris mastacanthus (1r) and *C. tangutica* (1r) were undamaged.

Cassinia fulvida (2r) was undamaged.

Castanea sativa.—The Spanish chestnut was very generally and very severely damaged, small and large trees, when the cold air was sufficiently deep, being equally affected. Damage was usually limited to the young shoots and, except in the case of young trees, a very good recovery was usually made. One detailed count was made in a plantation formed in 1924; all the trees lost the terminal shoot, but subsequently a very good recovery was made. A few reports were received of cases where this species was undamaged where other trees had suffered, but this was not of frequent occurrence. It was very noticeable that where Spanish chestnut was damaged all the trees were injured, unlike trees such as oak where there was a great deal of variation in the amount of damage from tree to tree. In many places Spanish chestnut took its share with oak and beech in producing the discoloured woodland scenes which were such a striking feature in the south of England for some time after the frost.

Catalpa.—This genus was generally severely damaged. The following records were received, all of severe damage :—*C. bignonioides* (3r), *C. duclouxii* (1r), *C. fargesii* (1r) and unspecified spp. (3r). In some cases the damage extended to the old wood. One record of a sheltered tree (unspecified species) with no damage was received.

Ceanothus.—No damage was reported on this genus; but the plants are mostly grown against walls or in sheltered situations. The species particularly referred to as undamaged were : *C. arnoldii* (1r), *C. dentatus* (1r), *C. floribundus* (1r), *C. rigidus* (2r), *C. thyrsiflorus* (1r) and *C. veitchianus* (2r).

Cercidiphyllum japonicum was generally severely injured; only from one area where the vegetation was very backward was it reported uninjured.

Cercis siliquastrum (5r) was variously reported as severely damaged, and undamaged. There is little doubt that in the case of this species damage is dependent on whether the tree is in leaf or not.

Chimonanthus fragrans (4r) was variously reported as severely damaged, moderately damaged and undamaged.

Cistus.—Unspecified spp. (2r) were reported undamaged; but *C. cyprius* (1r), *C. loretii* (1r) *and C. purpureus* (1r) suffered severe damage to the young shoots.

Cladrastis tinctoria (1r) was severely damaged.

Clematis armandi (1r), growing on a wall, was reported with slight damage to the young shoots.

Clerodendron fargesii (2r) was moderately to severely damaged, whereas *C. foetidum* (1r) suffered only slight injury to the leaves.

Cornus sanguinea (1r) was undamaged and unspecified spp. (5r) undamaged and slightly damaged.

Corokia cotoneaster (1r) was undamaged.

Coronilla emerus (1r) was undamaged.

Corylopsis.—Unspecified spp. (2r) were moderately and severely damaged.

Corylus avellana.—The hazel, like the hornbeam and the birch, is a very frost-hardy tree. In the majority of cases it escaped damage and was never reported with more than slight damage to the young leaves. It is of course often found as an understorey in oak woods and its escape might at first be attributed in part to shelter. Many of the reports, however, were of hazels growing in the open. *C. maxima atropurpurea* (2r) was also reported undamaged.

Cotoneaster frigida (1r) and unspecified species (3r) were undamaged.

Crataegus oxycantha L.—Hawthorn was not very much damaged, but it is not so hardy as hornbeam or birch. Severe damage to seedlings, of which many were killed, was reported in one case, and records of severe injury to hedges and individual trees were received. An unusally large number of reports referred to damage on the north or north-east side only, as if this species were particularly affected by cold winds. This may be merely a reflection of the fact that hawthorn is often grown in very exposed situations. In a few cases damage to the blossoms only was reported.

Cytisus.—This genus appears to be rather hardy, unspecified spp. (2r) being reported undamaged. Damage to the flowers only was recorded in the case of *C. purpureus* (1r) and unspecified spp. (1r). *C. battanderi* (2r) was reported moderately damaged in one case and undamaged in the other.

Daboecia.—Unspecified spp. (1r) were undamaged.

Danaë laurus (1r) was undamaged.

Daphne.—No damage was reported to *Daphne* spp. (3r) including *D. blagayana*, and *D. neapolitana.*

Daphniphyllum.—Moderate to severe injury was reported on unspecified spp. (3r).

Davidia involucrata was generally reported very severely injured. Under *D. involucrata* are here included Dode's three species *involucrata*, *vilmoriniana* and *laeta*, all of which were severely damaged.

Decaisnea fargesii (1r) had the young shoots severely cut back.

Desfontainea spinosa (1r), growing on a wall, was reported to have suffered moderate damage to the young shoots.

Deutzia.—Unspecified spp. (2r) had the young tips cut back. *D. gracilis* (1r) was reported with only the blooms injured.

Diervilla.—Unspecified spp. were reported with the young shoots severely cut back in four cases, with slight damage, and with injury to the flowers only.

Diospyros lotus (1r) and *D. virginiana* (1r) were both reported with the young shoots severely damaged, whereas the reputedly less hardy *D. kaki* (1r) was only slightly injured.

Dipelta floribunda (1r) had the young shoots severely cut back, whereas the more recently introduced *D. yunnanensis* (1r) was undamaged.

Drimys winteri (2r) was undamaged, or only very slightly injured, in one case at least it was on a wall.

Eccremocarpus scaber (1r), growing on a wall, was undamaged.

Elaeagnus macrophylla (1r) and *E. pungens aurea* (1r) were undamaged.

Emmenopterys henryi (1r) had very severe damage to the young shoots.

Enkianthus japonicus was severely damaged where exposed to the east.

Erica ciliaris (1r), *E. tetralix* (1r), *E. vagans* (1r), *E. veitchii* (1r), and unspecified spp. (1r) were all reported moderately damaged.

Eriobotrya japonica (1r) was undamaged.

Escallonia macrantha (2r) was the only species of this genus reported to have suffered damage. Its young shoots were severely cut back. The following varieties were undamaged :—E. C. F. Ball (1r), *E. exoniensis* (1r), *E. iveyi* (1r) and *E. montevidensis* (1r). Some of these were growing on walls. Unspecified spp. (2r) were also undamaged.

Eucalyptus coccifera (1r) and *E. gunnii* (1r) were undamaged.

Eucryphia pinnatifolia (5r) was undamaged; but *E. nymansay* (2r) suffered severe damage to the young shoots.

Euonymus.—Unspecified spp. (2r) and *E. alatus* (1r) were undamaged.

Exochorda grandiflora (2r) was undamaged.

Fabiana imbricata (3r) was undamaged and slightly damaged, and *F. violacea* (1r) undamaged.

Fagus sylvatica.—Of the broadleaved trees the beech was the most generally and most strikingly damaged. Unlike the ash, the oak, and the Spanish chestnut, which were turned a dirty black as a result of the frost, the beech assumed a bright brown autumn-like coloration. Partly for this reason, and partly because it is grown so often on chalk and limestone hills where the contrast in damage between the hilltops and the valleys was very marked beech provided the best indicator of the limits of the pooling of cold air. Frequently in valleys in the Chilterns and elsewhere damage would cease abruptly half way up a beech wood on a slope. The small beech in the nursery or recently planted in the forest were usually in the cold air near the ground and were often damaged very seriously. In a number of places they escaped because they were protected by artificial shelter in the nursery or natural shelter in the forest. Beech being a shade bearer is often used to underplant other species, such as ash, and in some situations of this kind the shelter overhead was sufficient to stop, or at least mitigate, the damage. Damage to unsheltered seedlings in the nurseries was particularly severe; in one a small bed of one-year-old beech was killed and losses of 50 and 33 per cent. in beds of the same age were also reported. The extent of the losses in young plantations can be seen from the figures given below (Table XXIX). Damage to large trees while more striking seldom did any permanent harm. In most cases beech trees were well in leaf at the time of the frost and few escaped because they were backward. Nevertheless there is considerable variation in the time of flushing of this species and the absence of damage on backward trees was noted in a few cases. Beech provided a very clear example of the effect of lateness brought about by transplanting during the preceding winter. In the same nursery, plants which had been moved in the winter of 1933–34, but not in that of 1934–35 were severely damaged, whereas those moved in the winter of 1934–35 escaped damage entirely.

Detailed counts of damage were made in a number of forest areas, and are set out in the following table :—

TABLE XXIX.

Beech.

Year of Planting.	Percentage of Trees in Damage Classes.						Height (feet).
	Little or no Damage.	Only side Shoots damaged.	Leaders damaged.	Some older Wood damaged.	Cut to the Base.	Dead.	
1927	—	—	17	79	4	—	1½
1927	19	—	43	38	—	—	4
1930	—	—	50	50	—	—	6
1930	34	30	32	1	1	2	2–3
1932	—	—	17	33	—	50	½–1
1933	50	6	7	3	3	31	½–1

Particularly noticeable is the large proportion of trees in which the old wood was damaged. The behaviour of this species at the forest phenological stations was curious. The worst damage occurred at Lynford (for temperatures see under *Larix europaea*, page 52) where all the plants were injured, and in 75 per cent. of them damage extended to the old wood. At Benmore 85 per cent. was damaged and at Nagshead 78 per cent., but the percentage with damage to the old wood is not known. The percentages damaged bear no relation to the temperatures in this case, for Nagshead was the coldest station, and Benmore the least cold during the frosts. The state of development of the beech is presumably responsible for these unexpected results.

Copper beech, *Fagus sylvatica purpurea*, was also frequently severely injured. In some areas it was less injured than the common beech but in others the reverse was the case and there are no real grounds for saying it is the hardier of the two. In comparing the total figures for these beeches given in the order of susceptibility to damage (page 87), it must be remembered that nearly all the records for copper beech refer to fair-sized trees, whereas a great many of those for common beech refer to young plantations or plants in nurseries.

Fagus sylvatica heterophylla (1r) was severely damaged, and *F. sylvatica pendula* (1r) slightly damaged.

Feijoa sellowiana (2r) was undamaged.

Ficus carica (1r) suffered severe damage to the young shoots.

Forsythia.—Unspecified spp. (1r) were undamaged.

Fraxinus excelsior.—The ash, like the beech and the oak, was very generally damaged. In many cases the coppice growth in the hedgerows had already made growths of six inches and over at the time of the frost, and these, hanging limp and black, made the damage rather striking, Plate III, fig. 1. On the other hand in parts of the country, particularly in the north of England and in Scotland, some of the trees had their buds still unbroken at the time of the frost and escaped injury. The damaged trees were very late in flushing, for the terminal buds which would have flushed first were dead. In other trees the frost seemed merely to delay flushing without apparently having caused any real damage. Even in June, in many parts of the country, large numbers of ash trees could be seen still in winter condition. Wherever they were in leaf, unless sheltered or in a very favoured situation they were injured, often severely. Although injury often extended to the old wood, there were few deaths except in very small plants, and even with those the death rates were much less than for beech. The ash has much better powers of recovery from frost than beech. The worst damage recorded was 30 per cent. killed in a bed of seedlings and 40 per cent. killed in a plantation formed in 1935.

Detailed counts from forest areas are set out in Table XXX.

TABLE XXX.

Ash.

Year of Planting.	Percentage of Trees in Damage Classes.						Height (feet).
	Little or no Damage.	Only side Shoots damaged.	Leaders damaged.	Some older Wood damaged.	Cut to the Base.	Dead.	
1920	3	20	73	4	—	—	3–10
1923	1	—	86	12	1	—	3–9
1925	1	—	92	7	—	—	3–7
1927	12	—	18	54	15	1	6
1929	3	—	83	12	2	1	2½–5
1930	8	—	88	—	2	2	1½–3
1932	—	—	79	1	15	5	2
1932	1	—	92	—	6	1	6
1932	2	4	86	—	2	5	1–3
1934	49	—	14	27	3	7	2

In ash there is usually a more definite leading shoot than in many other broadleaved trees, but unlike conifers, the leading shoots of ash flush at the same time as, or before, the side branches. Therefore it is only when the trees are tall enough for the tops of some to be out of the cold air near the ground that any considerable proportion is found with damage to side shoots only, as in the first example in the table above. In the phenological plots all the plants were damaged at Nagshead and Lynford, and 90 per cent. of them at Benmore, but there were no deaths. *F. excelsior pendula* (1r) was reported severely damaged.

Other Species of Fraxinus.—*F. americana* (1r) was moderately damaged. Many of the trees escaped damage owing to late flushing, but this was probably due to ill health rather than to any natural tendency to lateness. *F. ornus* (1r) was severely damaged.

Fuchsia riccartonii (2r) was reported moderately to severely damaged. *F. excorticata* (1r), growing on a wall, was reported with slight damage to the leaves.

Garrya elliptica (3r) was undamaged.

Genista aetnensis (2r) was reported undamaged and with severe damage to the young shoots. *G. hispanica* (1r) was undamaged.

Gleditschia.—Unspecified spp. (1r) were severely damaged.

Grevillea rosmarinifolia (2r) and *G. sulphurea* (1r) were both undamaged.

Griselinia littoralis (1r) was undamaged.

Halesia carolina (3r) was undamaged.

Hamamelis japonica arborea (2r) was reported undamaged and with moderate damage to the young shoots. *H. japonica flavopurpurascens* (1r) was reported undamaged, and *H. mollis* (3) undamaged and with moderate to severe damage to the young shoots and leaves.

Hedera helix, the common ivy, was damaged with surprising frequency, the young shoots being affected. It was injured with special severity when growing in exposed places, such as on fences and low walls.

Hedysarum multijugum (1r) was undamaged.

Helianthemum spp. (1r) were reported undamaged.

Hibiscus syriacus (2r) was reported undamaged and moderately damaged.

Hippophaë rhamnoides (2r) was undamaged and severely damaged, the latter beside the sea on the east coast.

Hydrangea hortensis acuminata (1r), *H. paniculata* (1r), *H. petiolaris* (1r), *H. sargentiana* (1r) and unspecified spp. (1r) all suffered severe damage to the young shoots.

Hypericum androsaemum (1r) and *H. hookerianum* (1r) were both cut right back. *H. moserianum* (2r) was reported undamaged and with damage to the young leaves. *H. patulum* varieties (1r) were undamaged.

Ilex aquifolium and its varieties were frequently damaged. Usually only the young shoots were affected but one case was reported where damage extended to the old wood.

Illicium religiosum (1r) suffered moderate damage to the young shoots.

Jasminum primulinum (1r) and unspecified spp. (1r) were undamaged. The former was growing on a wall.

Juglans.—Few trees were more generally or severely injured by the May frosts than the walnut. Out of 108 reports received 100 were of severe damage. Probably the reports mostly refer to *J. regia*; in many of them it is specified, but a large number mention merely walnut, and there can be no certainty that *J. nigra* is not referred to. It is almost certain that some of the records do relate to *J. nigra*, but only one record, of severe damage, was received in which it was specifically mentioned. Damage often extended to the old wood and in large trees recovery was inclined to be slow. In small trees, unless they were in ill health from other causes, vigorous shoots were usually soon produced, but one record of a 20 per cent. loss among two-year-old seedlings was received. It is not known to what extent the nut crop was affected by the frost, but on the worst injured trees it was probably lost. *J. sieboldiana* (1r) was reported very severely injured.

Kalmia angustifolia (1r), *K. latifolia* (1r) and unspecified spp. (2r) were undamaged.

Kerria japonica flore pleno (1r) was undamaged.

Laburnum vulgare was frequently reported with damage to the flowers. In only two cases was damage done to the leaves and in both it was very slight. *L. alpinum* (1r) and *L. vossii* (1r) were undamaged.

Laurus nobilis (2r) was undamaged and very severely damaged.

Lavandula.—Unspecified spp. (1r) were undamaged.

Leptospermum scoparium (2r) was reported undamaged, and with severe damage to the young shoots.

Leycesteria formosa (1r) was undamaged.

Ligustrum.—Little damage appears to have been done to privet, though severe damage to young shoots on a hedge, probably of *L. vulgare* or *L. ovalifolium* was reported in one case. *L. japonicum* (1r) suffered slight damage to the leaves, but *L. vulgare* (1r), *L. ovalifolium* (1r), *L. ovalifolium aureum* (1r) and *L. delavayanum* (1r) were all undamaged.

Liquidambar styraciflua (4r) was undamaged in three cases, and moderately damaged in the fourth.

Liriodendron tulipifera.—The tulip tree was generally severely damaged, but usually made a good recovery. In a young plantation formed in 1931 nearly half the trees suffered injury to the old wood and most of these were cut back to ground level, but recovery was very satisfactory; in one case the 1935 shoot had equalled the previous height of the tree by the end of the season.

Lonicera nitida was moderately and severely damaged in seven cases which detracts somewhat from its value as a hedging plant. *L. periclymenum* (1r), *L. pileata* (1r), *L. standishii* (1r) and unspecified spp. (1r) were undamaged.

Maackia amurensis (1r) was severely damaged.

Magnolia.—Severe injury to the young shoots and leaves was reported on *M. acuminata* (1r), *M. conspicua* (3r)—in one case the old shoots were damaged, *M. cordata* (1r), *M. glauca* (2r), *M. grandiflora* (2r)—undamaged in one case, *M. lennei* (3r)—moderately damaged in one case and very slightly in another, *M. obovata* (1r), *M. parviflora* (4r)—in one case the tree was killed, *M. sinensis* (1r), *M. soulangeana* (5r)—moderately damaged in one case and slightly in another, *M. watsonii* (1r), and unspecified spp. (6r). *M. obovata nigra* (1r) was slightly damaged, *M. kobus* (1r) and *M. stellata* (3r) undamaged.

Melicytus ramiflorus (1r) was undamaged.

Meliosma. Unspecified spp. (1r) were reported with very severe damage to the young shoots.

Morus nigra (4r) suffered damage varying from moderate to very severe, and unspecified spp. (1r) were moderately damaged.

Myrtus communis (3r) was undamaged in two cases and moderately damaged in the third, *M. communis tarentina* (1r), *M. communis mucronata* (1r), and *M. luma* (1r) were undamaged.

Nothofagus.—This genus proved hardier than might have been expected. The only damage reported was on *N. procera* (1r) which suffered severe damage to trees six to eight feet high, 30–40 per cent. of which died back, many of them to the ground. In the stems of plants not cut back numerous frost cracks appeared later in the season. In the same situation *N. obliqua* and *N. dombeyi* were undamaged. Apart from these records *N. antartica* (1r), *N. obliqua* (1r) and *N. cunninghami* (1r) were reported undamaged.

Nyssa sylvatica (1r) was undamaged.

Olea europaea (2r) was undamaged, in one case at least it was growing on a wall.

Olearia gunniana (2r), *O. macrodonta* (1r) and *O. haastii* (1r) were undamaged.

Osmanthus forrestii (1r), *O. fortunei* (2r) and unspecified spp. (1r) were reported with moderate damage to the young shoots.

O. delavayi (2r) was undamaged, and severely damaged.

Oxydendrum arboreum (2r) suffered severe damage to the young shoots.

Ozothamnus purpurascens (1r) was undamaged.

Paeonia moutan (1r) was slightly damaged.

Parrotia persica (4r) was undamaged in three cases and moderately damaged in one.

Paulownia imperialis (3r) was undamaged and moderately damaged. *P. fargesii* (1r) was severely damaged.

Pernettya mucronata (1r) was moderately damaged.

Phellodendron japonicum (1r) and *P. sachalinense* (1r) were undamaged, but both were growing in an area where damage was not very severe.

Philadelphus.—Damage in this genus was very variable. *P. delavayi* (1r) was reported with severe damage to the young leaves, and unspecified spp. (5r) with no damage, with slight damage to the flower buds, and with severe damage to the young shoots.

Phlomis fruticosa (1r) was undamaged.

Photinia serrulata (1r) was undamaged.

Phygelius capensis (1r) was undamaged.

Phyllostachys nigra (1r) had very slight damage to the leaves.

Pieris. Severe damage to the young shoots was reported on *P. formosa* (2r), *P. forrestii* (2r) and *P. japonica* (2r), while *P. taiwanensis* (1r) was undamaged.

Pittosporum buchananii (1r), *P. undulatum* (1r) and *P. tenuifolium* (1r) were reported undamaged, but *P. tenuifolium* was to some extent sheltered.

Plagianthus lyallii (1r) suffered moderate damage to the young shoots.

Platanus. The plane was frequently severely damaged. Many of the reports do not state the species and record damage varying from none to severe. Apart from these *P. orientalis* (5r) was reported with severe damage and *P. acerifolia* (2r) with damage varying from none to severe.

Polygonum baldschuanicum (3r) had slight to moderate damage done to the young shoots.

Populus. Comparatively little damage was done to the poplars. A great many of the reports received did not give the species and in the table on page 87 these have been combined with the reports from individual species under the general heading *Populus.* Damage where it occurred was usually very slight, the leaves or some of the young shoots being affected. A few cases of more severe damage were recorded both on unspecified species and on various species the names of which are known.

Two detailed counts of damage are given below. The species in these is not known, but it was probably *P. serotina.*

TABLE XXXI.

Poplar.

Year of Planting.	Percentage of Trees in Damage Classes.						Height (feet).
	Little or no Damage.	Only side Shoots damaged.	Leaders damaged.	Some older Wood damaged.	Cut to the Base.	Dead.	
1931–32	65	23	12	—	—	—	4–6
1935	93	—	2	—	3	2	5½

In the reports giving the name of the species severe damage was recorded on *P. lasiocarpa* (1r) and *P. alba* (1r). In the case of *P. tremula* severe damage was done in only two reports out of six, the other four showing no damage. Moderate damage was recorded on *P. nigra italica* in three cases out of seven, there being no damage in the remainder, and on *P. serotina* (4r), three reports were of lack of damage. Slight or very slight damage was recorded on *P. angulata erecta* (1r), *P. eugenei* (2r)—one case was of no damage, and *P. canescens* (3r)—two cases were of lack of damage. No injury was recorded on *P. generosa* (1r), *P. nigra* (3r), *P. robusta* (1r) and *P. trichocarpa* (3r).

Prunus.—A large number of reports was received with regard to this genus and in general it seems to have escaped the frost lightly. The greatest exception to this was *P. laurocerasus*, the cherry laurel. There is doubt about some of the reports for this species, for they are included on the assumption that " laurel ", in the correspondence, refers to this shrub, rather than to *P. lusitanica*, the Portugal laurel, or *Laurus nobilis*, the bay laurel. This assumption is probably justified in most cases, but may have led to the inclusion of a few reports that in reality refer to other species. On this assumption *P. laurocerasus* was very generally severely damaged, though a few records of slight damage were received. The Portugal laurel, *P. lusitanica*, judging by the six definite records received, was less generally damaged, for only two of them were of severe injury. *P. laurocerasus rotundifolia* (1r) and *P. laurocerasus caucasica* (1r) were severely injured.

Prunus spinosa suffered very little injury, though one report of moderate and one of slight damage were received. Very severe damage was reported on *P. grayana* (1r). *P. cerasus* (4r) suffered damage varying from moderate to none. Slight damage confined to the flowers, was reported on *P. sargentii* (1r), *P. serrulata sekiyama* (1r) and *P. padus* (2r)—undamaged in one case, while on *P. avium* (2r) the young fruits were damaged in one case but no damage done in the other. Complete absence of damage was reported on *P. amygdalus* (2r), *P. cerasifera blireiana* (1r), *P. cerasifera pissardii* (3r), *P. japonica* (1r), *P. persica* varieties (1r) and *P. triloba* (1r).

Punica granatum (2r) was reported undamaged and with severe damage to the young shoots.

Pyrus.—Very little damage indeed was done among the ornamental or wild species of this genus, *P. malus* (2r) was, however, reported severely damaged, in one case 50 per cent. of young plants being killed. Severe damage was also reported in two cases on *P. aucuparia*, the mountain ash, but nearly all the records for this species were of lack of damage. *P. torminalis* (2r) was severely damaged in one case, but undamaged in the other. Slight damage was recorded on *P. baccata* (1r) and in two reports on *P. aria*, the whitebeam, but in the latter nearly all the records were of absence of damage. Complete absence of damage was reported on *P. eleyi* (1r), *P. intermedia* (1r) and *P. sorbus* (1r).

Quercus.—In most reports no distinction was made between *Q. pedunculata* and *Q. sessiliflora* and they will be considered together. The few cases in which the specific name was given, do not suggest that there is any real difference in frost susceptibility. The oak, like the ash, beech and Spanish chestnut, was frequently and generally damaged. The blackening of oak woods and of the isolated hedgerow trees was perhaps the most striking evidence of the severity of the frosts, Plate IV, fig. 2. Oak provided fewer examples of the pooling of cold air in valleys than did beech, but some remarkable evidence of the limits of the cold air near the ground could be seen on isolated trees. The foliage on the lower branches was often withered and dead, whereas the top of the tree was quite unharmed (*see* Frontispiece). This phenomenon was not uncommon on other large trees, but was most frequently seen on oak.

Although injury was very general on trees of all ages, there were few reports of really serious losses. The effect on large trees was usually only temporary and in most cases small trees made a very good recovery. The worst case reported was a loss of 68 per cent. in a plantation formed in 1935, but this was exceptional.

Detailed counts were made in a number of forest areas, and a typical selection of these is set out in the following table :—

TABLE XXXII.

Oak.

Year of Planting.	Percentage of Trees in Damage Classes.						Height (feet).
	Little or no Damage.	Only side Shoots damaged.	Leaders damaged.	Some older Wood damaged.	Cut to the Base.	Dead.	
1924	—	—	100	—	—	—	4
1928	1	—	99	—	—	—	4
1928	12	7	31	50	—	—	6
1930	1	—	97	1	—	1	2
1930	6	—	94	—	—	—	1–2½
1931	—	—	90	10	—	—	1
1931	18	15	63	—	—	4	2–3½
1932	6	4	87	—	1	2	1
1933	—	95	3	—	—	2	1

In the above table the large number of trees in which the leading shoot was frosted is very noticeable. At the forest phenological stations all the oaks were damaged in each case, and at Nagshead 12 per cent. died. These were the only deaths reported from any of the stations among the six species used, *viz.*, ash, oak, beech, Douglas fir, Sitka spruce, and European larch.

The variation in injury between individual trees was very marked. This had nothing to do with the time of flushing as oak was practically everywhere in leaf at the time of the frost. In some cases it was suggested that the oaks which had been in leaf longest escaped, but as already pointed out there are certain difficulties in accepting this assumption. In experiments carried out with oak in a refrigerator a good deal of difference was found to exist between individual plants, irrespective of their stage of development. It is probable that this is the case in nature and that certain oaks are hardier than others for some physiological reason not dependent on their stage of development.

Other Species of Quercus.—*Q. rubra* and *Q. coccinea* were damaged to about the same extent as the common oak. *Q. cerris* (5r) and *Q. ilex* (2r) were reported with damage varying from none to severe; *Q. mirbeckii* (1r), growing under quite heavy shelter, suffered moderate damage, and *Q. palustris* (1r) slight damage.

Rhamnus cathartica (1r) was reported undamaged and *R. frangula* (1r) very slightly damaged.

Rhododendron.—A good deal of information has been collected with regard to this large genus, but it is still very incomplete. Many areas reported damage to leaves, young shoots, and flowers, and such damage was often severe. In a number of cases injury was restricted to the flowers. Particularly severe damage occurred on azaleas. In two cases mention is made of Himalayan rhododendrons as having suffered. *R. ponticum* (3r) was among the species damaged, in one case even the old shoots being injured, but in another case it was reported undamaged. *R. hirsutum* (1r) was undamaged. Severe injury to the young shoots occurred on the following species (1r in each case), but it is obvious that this is far from a complete list:—*R. augustinii*, *R. barbatum*, *R. decorum*, *R. fortunei*, *R. haematocheilum*, *R. heliolepis*, *R. irroratum*, *R. loderi*, *R. moupinense*, *R. niphargum*, *R. racemosum*, *R. rubiginosum*, *R. schlippenbachii*, *R. trichocladum*, *R. wardii*, *R. williamsianum* and *R. yunnanense*.

Rhodotypes kerrioides (1r) was reported undamaged.

Rhus.—Many of the records for this genus cannot be referred to their species, as they were reported merely under the name sumach, which is used for the majority of the commoner species. Most of the unspecified records were of severe damage. Severe damage was recorded on *R. cotinoides* (2r)—moderately damaged in one case, *R. cotinus* (3r)—slightly damaged in one case, *R. cotinus atropurpurea* (3r)—moderately damaged in one case, *R. typhina* (2r)—moderately damaged in one case, and *R. typhina laciniata* (1r), were slightly damaged.

Ribes sanguineum (1r) and *R. speciosum* (1r) were both undamaged.

Robinia.—Records for this genus generally refer to it merely as *Robinia*, false acacia, or even more frequently, acacia. There is obviously a possibility of error in referring all these to *Robinia pseudacacia*. Out of 38 reports 36 were of severe or moderate damage. In three cases varieties were referred to, *R. pseudacacia* *bessoniana* (1r) being moderately, and *R. pseudacacia decaisneana* (1r) and *R. pseudacacia angustifolia* (1r) being severely damaged. Severe damage was also reported on *R. hispida* (1r).

Rosa canina (1r), and *R. rubrifolia* (1r) were undamaged; moderate damage was recorded on *R. moschata* (1r) and *R. moyesii* (1r).

Rosmarinus officinalis (1r) was undamaged.

Rubus.—Unspecified spp. growing wild were severely damaged in one case and undamaged in another. There is little doubt that they were generally not much damaged.

Ruscus aculeatus (1r) was undamaged.

Salix.—A large number of reports was received for various willows, and these indicate quite definitely that they are generally very hardy. In those named *S. magnifica* (1r) was very severely damaged, *S. vitellina pendula* (1r) had damage varying from none to severe, *S. vitellina britzensis* (1r) and *S. babylonica* (2r) were slightly damaged. *S. caprea* (5r), *S. daphnoides* (1r) and *S. vitellina* (1r) were undamaged.

Sambucus nigra (2r) was undamaged and very slightly damaged. Various species of elder (5r) were reported undamaged, slightly damaged and severely damaged.

Sassafras officinale (1r) suffered severe damage to the young shoots.

Schizandra. Unspecified spp. (1r) were undamaged.

Senecio laxifolius (1r) was undamaged.

Skimmia japonica (1r) was undamaged.

Solanum crispum (2r) and *S. jasminoides* (1r) were undamaged.

Spartium junceum (1r) was undamaged.

Spiraea.—Unspecified spp. (2r) were reported undamaged and slightly damaged. *S. japonica* Antony Waterer (1r) and *S. japonica* (1r) received moderate damage to the young shoots. Severe damage was recorded on *S. aitchisoni* (1r), *S. arborea* (1r), *S. lindleyana* (1r) and *S. sorbifolia* (1r).

Stachyurus praecox (2r), *S. chinensis* (1r) and unspecified spp. (1r) were all reported with severe damage to the young shoots.

Stephanandra flexuosa (1r) and *S. tanakae* (1r) were undamaged.

Stewartia.—Unspecified spp. (1r) were moderately damaged. Severe damage to the young shoots was recorded on *S. sinensis* (1r) and *S. pseudocamellia* (1r).

Styrax.—Unspecified spp. (3r) and *S. japonicum* (1r) were reported with very severe injury to the young shoots.

Symphoricarpus racemosus (2r) was reported undamaged and with severe damage to the young shoots. *S. orbiculatus* (1r) and *S. orbiculatus variegatus* (1r) were undamaged.

Syringa.—Damage to this genus was very variable. Unspecified spp., probably mostly *S. vulgaris* varieties, were reported undamaged and with slight damage to the leaves or to the flowers, and in one case with severe damage to the young leaves. There was slight damage to the young shoots on *S. yunnanensis* (1r), and severe damage on *S. velutina* (1r), *S. emodi* (1r) and *S. komarowii* (1r).

Tamarix pentandra (1r) and *T. hispida* (1r) were both severely damaged. In *T. hispida* the damage extended to the old shoots. Unspecified spp. (1r) also received severe damage.

Tecoma grandiflora (2r) was undamaged, but in one case it was partially sheltered. *T. radicans* (2r) was severely damaged and undamaged, but in the latter case it was partially sheltered.

Tilia.—Only one of the many reports on limes gave the species. This was of lack of damage on *T. cordata.* The remaining reports probably mostly refer to *T. vulgaris,* but some may refer to the less commonly planted species such as *T. cordata, T. euchlora* and *T. petiolaris.* Only one report of severe and one of moderate damage were received, all the remainder being of slight damage or lack of damage, most of them the latter. Of the commoner large trees lime and elm escaped most lightly from the frosts.

Ulmus.—Only one instance of severe damage to elm was recorded and this was to small hedgerow trees, larger trees in the same area being undamaged. Slight damage occurred in a number of cases, but most of the reports were of total absence of injury. The bulk of the reports gave no specific names, and in Table XXXIII all the records have been placed under the one heading *Ulmus* spp. *U. montana* (5r) and *U. stricta* (4r) received damage varying from slight to none, while *U. campestris* (2r), *U. montana pendula* (1r) and *U. parvifolia* (1r) were undamaged.

Vaccinium mortinia (1r) was undamaged.

Veronica hulkeana (1r) was undamaged.

Viburnum.—This genus does not seem to have been severely affected. Damage varying from severe to none was reported on *V. tinus* (4r). Moderate damage was recorded on *V. betulifolium* (1r). *V. tomentosum mariesii* (2r) was moderately damaged in one case, but undamaged in the other. *V. carlesii* (3r) and *V. lantana* (3r) were both reported slightly damaged in one case but undamaged in the other two. *V. opulus* (5r) was reported with very slight damage in one case but undamaged in the others. *V. tomentosum plicatum* (2r) had the flowers injured in one case but was undamaged in the other. *V. burkwoodii* (1r), *V. fragrans* (2r), *V. rhytidophyllum* (1r), *V. tomentosum* (1r) and unspecified spp. (3r) were undamaged.

Vinca major (1r) and *V. minor* (1r) were undamaged.

Vitis.—Very severe damage occurred on *V. armata* (1r), *V. henryana* (1r), *V. megalophylla* (1r) and *V. vinifera* (1r), and moderate damage on *V. inconstans* (1r), *V. vitacea* (1r) and unspecified spp. (3r).

Wistaria.—Damage to this genus was very irregular. It varied from moderate injury to the young shoots to a complete absence of damage. It is probable that most of the plants were on walls, and variations in aspect may well have made a good deal of difference. In several cases only the flowers were damaged.

Yucca filamentosa (1r), *Y. gloriosa* (1r) and *Y. recurvifolia* (1r) were reported undamaged.

Zelkova crenata (1r) was very slightly damaged.

Order of Susceptibility to Damage.

Table XXXIII has been compiled on the lines indicated on page 65 to show the order of susceptibility of the more important broad-leaved species.

TABLE XXXIII.

Species.	Percentage of Reports in Damage Classes.					Total No. Reports.	Severity Index.
	Very Severe.	Severe.	Moderate.	Slight.	None.		
Juglans spp.	7	85	4	3	1	108	294
Robinia pseudacacia	5	82	8	—	5	38	282
Acer palmatum	16	67	6	3	6	31	280
Liriodendron tulipifera	13	57	17	13	—	23	270
Fraxinus excelsior	5	61	11	11	12	255	262
Alnus oregona	33	29	—	29	7	24	248
Castanea sativa	5	60	17	12	6	127	246
Prunus laurocerasus	—	69	8	19	4	26	242
Quercus sessiliflora and *pedunculata*	6	52	16	17	9	276	229
Fagus sylvatica	7	48	17	17	11	347	223
Fagus sylvatica purpurea	11	33	11	37	8	27	202
Aesculus hippocastanum	1	24	17	34	24	80	144
Acer pseudoplatanus	1	29	11	29	30	126	142
Crataegus oxycantha	4	23	14	14	45	22	127
Populus spp.	—	13	6	20	61	80	71
Pyrus aucuparia	—	9	—	17	74	23	53
Betula alba ..	2	2	2	14	80	62	32
Corylus avellana	—	—	—	32	68	22	32
Carpinus betulus	—	8	—	5	87	38	29
Tilia spp. ..	—	2	2	17	79	45	27
Ulmus spp. ..	—	1	—	19	80	94	22

In this table the species have been divided into three groups. The first contains the most susceptible—those that were damaged in all places where frost was at all severe, and were often very badly injured. The second, contains the moderately susceptible—those that were sometimes damaged but seldom severely. The third, consists of the hardy species, usually only damaged in particularly unfavourable situations.

The broadleaved trees for which more than five but less than 20 records are available are set out in Table XXXIV, but in this case the number of records in each damage class is given.

TABLE XXXIV.

Species.	Number of Reports in Damage Classes.					Total Number of Reports.
	Very Severe.	Severe.	Moderate.	Slight.	None.	
Acer campestre	—	1	3	2	8	14
Acer platanoides ..	—	—	—	—	6	6
Ailanthus glandulosa ..	1	6	1	—	1	9
Alnus glutinosa ..	—	2	—	1	3	6
Alnus incana	2	1	3	5	4	15
Hedera helix	1	1	6	2	1	11
Ilex aquifolium ..	1	2	3	1	3	10
Laburnum vulgare ..	—	—	—	15	1	16
Prunus lusitanica ..	—	2	—	3	1	6
Prunus spinosa ..	—	—	1	1	5	7
Pyrus aria	—	—	—	2	13	15
Quercus coccinea ..	1	3	—	2	—	6
Quercus rubra	1	6	3	1	3	14

In addition to literature already referred to in the chapter on conifers, a paper by Ramsay[37] relating to the frost of 17th May, 1871, gives details of damage to a number of broadleaved trees in the neighbourhood of Glasgow and is included below. In Table XXXV are set out the estimates of severity given by the various authors, using the abbreviations " Sev." for severe, " Mod." for moderate, " Sl-N." for slight to none.

Most of the observations set out in this table agree fairly well with those made in this country after the frosts of May 1935. Somerville's classification of *Castanea sativa* as only slightly damaged is curious. Ramsay's record of absence of damage on ash and oak is explained as being due to the fact that the trees were not in leaf at the time of the frost. In the group containing *Aesculus* and *Acer pseudoplatanus*, as might be expected, there is a mixture of all three damage classes. In the frosts of May 1935, injury to these species was very variable from place to place. In the hardy group it is surprising to find so many papers of previous years reporting moderate damage on elm, which in May 1935, was the hardiest of broadleaved trees. The inclusion of *Acer platanoides* among the severely damaged species is also remarkable.

TABLE XXXV.

Species.	Ramsay.	Somerville.	Roth.	Provis.	Schädelin.	Borgmann and Funk.	Greenfield.
Juglans	Mod.	—	Sev.	—	Sev.	Sev.	—
Robinia pseudacacia	—	—	Sev.	Sev.	—	Sev.	—
Acer palmatum ..	—	—	Mod.	—	—	—	—
Liriodendron tulipifera	—	—	Sev.	—	—	—	—
Fraxinus excelsior ..	Sl-N.	Mod.	Sev.	Sev.	Sev.	Sev.	Sev.
Castanea sativa ..	Sev.	Sl-N.	Sev.	Sev.	—	Sev.	Sev.
Prunus laurocerasus	Mod.	—	—	—	—	—	—
Quercus sessiliflora and *pedunculata*..	Sl.-N.	Sev.	Sev.	Sev.	Mod.-Sev.	Sev.	Sev.
Fagus sylvatica ..	Sev.	Sev.	Sev.	Sev.	Sev.	Sev.	Sev.
Fagus sylvatica purpurea	Sev.	—	Sev.	—	—	—	—
Aesculus hippocastanum	Sl-N.	Sl-N.	Sev.	—	—	Sl-N.	—
Acer pseudoplatanus	Mod.	Mod.	Sev.	—	Mod.	Mod.	Mod.
Crataegus oxycantha	Sl-N.	—	—	—	—	Sl-N.	—
Populus spp. ..	Sl-N.	Sl-N.	Mod.	Sl-N.	—	—	Sl-N.
Pyrus aucuparia ..	Sl-N.	Sl-N.	Sl-N.	—	—	Sl-N.	—
Betula	—	—	Sl-N.	Sl-N.	—	Sl-N.	Sl-N.
Corylus avellana ..	—	Sl-N.	—	—	—	Sl-N.	—
Carpinus betulus ..	—	Sl-N.	—	Sl-N.	—	Sl-N.	Sl-N.
Tilia	Sl-N.	Sl-N.	—	—	—	Mod.	—
Ulmus	—	Mod-N.	Sl-N.	Sl-N.	Mod.	Sl-N.	Mod.
Acer campestre ..	Sl-N.	—	—	—	—	—	—
Acer platanoides ..	—	—	Sev.	—	—	Mod.	—
Ailanthus glandulosa	—	—	Sev.	—	—	Sev.	—
Alnus glutinosa ..	—	—	Mod.	—	—	Sl-N.	Sl-N.
Alnus incana ..	—	—	Mod.	—	—	Sl-N.	—
Laburnum vulgare ..	Mod.	—	Sev.	—	—	—	—
Prunus lusitanica ..	Mod.	—	—	—	—	—	—
Pyrus aria	Sl-N.	—	—	—	—	—	—
Quercus coccinea ..	—	—	Sev.	—	—	—	—
Quercus rubra ..	—	—	Sev.	—	—	Mod.	—

Only two broadleaved species, oak and beech, have been used in experiments with the refrigerator. The critical temperatures for these for May were *Quercus* 21–26° F. and *Fagus sylvatica* 22–24° F. The variation in the figures for *Quercus* may be due to differences between individual trees. The figures for beech are surprisingly low considering its susceptibility to spring frost damage.

Though there is a good deal of variation in the time of flushing in many of the species, there is nothing so definite as the late and early flushing races of Norway spruce, it is therefore doubtful whether breeding and selection for frost resistance have such possibilities for broadleaved trees as they have for conifers.

SILVICULTURAL ASPECTS OF SHELTER AGAINST FROST.

It is a matter of common observation that frost damage can often be lessened or even prevented entirely by some form of shelter. The conditions under which different forms of shelter are effective are a matter of much discussion and it may be useful to consider what evidence the recent late frosts provide on this question. Broadly speaking, any substance interposed between the plant and the sky may be regarded as shelter, hence, as trees in economic planting are usually small, grass and other low herbage are included in the observations below.

It is convenient to consider shelter under the following headings:—

Coarse herbage and small woody plants.
Low woody shrubs such as gorse or broom.
Scattered coppice and small trees.
Snow.
Use of an existing tree crop as shelter; this may be either coppice or high forest.
The shelter crop is planted with and grows up with the plants to be protected.
The shelter crop is planted in advance.
Artificial shelter over nursery beds.

Coarse Herbage and small woody Plants.—The most common type of ground cover on newly planted areas is herbage of some sort, the character of which varies according to the soil and situation and the treatment which the soil has received. On a high chalk down it may consist of a thick turf in which the finer grasses predominate. If the down was arable land before afforestation, the soil cover will be comparatively sparse with coarser plants such as wild parsnip and scabious predominating. In a moist valley bottom a rank vegetation of tussock grasses, with iris, spiraea and other tall moisture-loving herbs may come up after enclosure and planting. On the more mountainous and moorland areas, small woody plants such as heather and bilberry commonly form a large part of the ground cover and may conveniently be considered here with the herbage.

The amount of shelter provided by short plants depends largely on their height in relation to the height of the tree. Usually this form of shelter is so low that only the small, recently planted tree can be said to receive protection from it. This is illustrated by counts made in weeding experiments carried out on the downs near Friston, Sussex, in connection with the establishment of beech (Table XXXVI). In each experimental plot the weeds, *i.e.*, grasses and other plants in the herbage, were removed from one half but left in the other. The plots were only laid out in the winter of 1932–33 and the plants were still quite small at the time of the 1935 frost.

TABLE XXXVI.

Small Beech at Friston.

Plot.	Treatment.	Percentage of total Number (May, 1935).			
		Badly frosted.	Moderately frosted.	Slightly frosted.	No Damage.
A	Weeded	64·5	31·0	3·8	0·7
	Unweeded	51·5	35·9	10·2	2·4
B	Weeded	96·4	2·1	—	1·4
	Unweeded	92·3	3·2	1·3	3·2
C	Weeded	99·3	0·7	—	—
	Unweeded	64·7	14·3	16·2	4·8
D	Weeded	10·9	3·6	23·6	61·8
	Unweeded	4·2	2·1	12·5	81·2

Plot A in the above table was situated on a slope on relatively high ground and was one of the less severely damaged. In Plot B situated a little lower and in a slight hollow, very few of the plants escaped damage. In each of these the situation is one of the main factors controlling the amount of damage.

The effect of a large number of small and probably backward plants is shown by Plot C, which needed much beating-up in 1933–34 and thus in May 1935, included many small plants established only one year and more or less covered by coarse herbage in the unweeded section. The relatively greater protection received by the small and more recently established plants and their more backward state probably account for the smaller amount of damage in the unweeded plot.

While tall, coarse herbage which entirely covers the plants is capable of providing efficient shelter from frost for quite small trees, the danger from smothering, owing to the collapse of the dead, winter herbage on top of the plant, is so great that in many cases it may be as bad to leave the cover as to remove it and expose the plants to frost damage. If the overhead cover is removed, side protection only is given but this is of little avail even to a very small plant. When plants are larger so that their tips project through the herbage, this not only ceases to provide protection, but even increases the danger of injury.

Meteorological observations carried out by Staudacher[44] and other workers have shown that on a clear cold night the temperature is appreciably lower at the tips of the grass than it is at ground level or at a few feet above ground. A small plant with its shoots at the level of the grass tips is thus in the coldest stratum of the air. Even a sparse covering of grass may have this effect as is shown in Table XXXVII below. The observations were made at Cranwich in Norfolk at irregular intervals between 21st May and 30th June, 1935.

TABLE XXXVII.

Minimum Temperatures over

Bare Soil.	*Sparse Grass.*	*Difference.*
° F.	° F.	° F.
29	28	1
36	35	1
35	35	0
23	21	2
27	25	2
30	29	1

The maximum difference of two degrees indicated in the table is quite enough to make a considerable difference in the amount of damage received.

It may be asked what is the value of the shelter provided during the spring by broadleaved plants such as bracken. It is clear that a broad-spreading leaf or frond will help to prevent the loss of heat by radiation from anything which it covers and to this extent useful protection may be expected. That this is so is indicated by the temperatures shown in Table XXXVIII. In both cases unscreened grass minimum thermometers were used, placed at one foot above ground level. The temperatures in this table were taken in June 1935 at Snake Wood, Lynford and at Didlington, both in Norfolk.

At Lynford the grass herbage consisted of *Festuca, Poa, Holeus, Koeleria,* etc. and at Didlington of pure *Festuca ovina.*

TABLE XXXVIII.

At Lynford.			At Didlington.		
Under Bracken.	Over Grass.	Difference under Bracken.	Under Bracken.	Over Grass.	Difference under Bracken.
° F.	° F.	° F.	° F.	° F.	° F.
38	37	+1	55	56	−1
39	38	+1	56	57	−1
43	43	0	43	41	+2
48	48	0	40	39	+1
40	40	0	38	37	+1
52	53	−1	38	35	+3

In May the bracken fronds are not so fully developed as in June, in fact in mid-May 1935, they were up but mostly still uncurled. The amount of protection given would, therefore, be much less than is indicated by the above figures; where the bracken was quite uncurled it would be negligible (Fig. IV). Any protection given at this time would only be effective in saving the plant from injury if the frost was very slight.

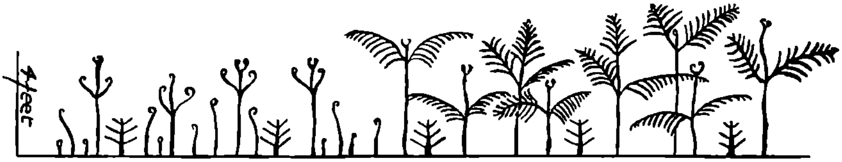


FIG. IV.—Diagram illustrating shelter by bracken when in curl and after expansion.

Short heather or bilberry may be expected to act in the same was as rather dense grass. Appreciable shelter is afforded beneath the canopy of a mass of either of these, but the low, dense cover given cannot be allowed to remain over the trees.

Low Shrubs as Shelter.—When afforesting heath or waste land, woody plants such as gorse or broom not infrequently occur which reach a height of about two to five feet. Occasionally heather is sufficiently tall to be included here. If the locality is one which is subject to severe frosts, it may be thought worth while to retain at least a part of this cover in the hope that it may afford protection to the small trees. Observations showed that shelter of this type was not often effective. The reason is that the interplanted trees are left too open to the sky and thus receive little or no shelter during radiation frosts.

An example of such shelter can be given from Friston, Sussex, where in the season 1932–33 beech was planted experimentally in a dense patch of gorse in a high-lying open situation (Plot D, Table XXXVI, page 91). Some of the plants were left under the gorse in cover too dense for good growth; some were freed from overhead shade, but left with side protection. The assessment in the table shows that an appreciable degree of protection was given in the unweeded section. At this forest also, and in a bad situation, common alder, which is one of the hardier trees, had its leaves moderately damaged in the open, but escaped injury beneath broom 10 feet high. At Swaffham in Norfolk, a dense growth of privet was reported as having effectively sheltered Douglas fir planted in 1929; on the other hand at Clashindarroch, Aberdeenshire, dense gorse proved useless as shelter.

These few observations show that low shelter of this type may give effective protection but much undoubtedly depends on its situation.

Scattered Coppice and small Trees.—When a woodland area has been cleared previous to replanting any scattered small trees which may remain standing, or which, together with coppice shoots, come up before planting has begun, are sometimes left to provide shelter. Several examples of this type of open shelter were observed after the frosts of May 1935, but there was no evidence of any effect on the amount of frost damage (Plate VII, fig. 1).

Shelter by Snow.—During the May frost 1935, four to six inches of snow fell in some parts of Britain and this proved to be sufficient fully to cover small trees. When so covered they were effectively protected from injury, but on the other hand, any part of a plant standing above the snow was particularly liable to be damaged because of the low temperatures occurring at the surface. Snow is a bad conductor of heat owing to the large amount of air which it holds, hence its action in keeping out frost.

The standing Crop as Shelter.—The usefulness and the type of shelter provided by standing trees depend largely on their height and density and on the species. Height is important in that this decides whether overhead or side shelter is possible and, in the case of side shelter, it largely determines the extent to which plants are screened. On density depends the provision of a complete or broken canopy; on the species depends largely the amount of shelter provided by any particular height and density of stand. The more densely crowned evergreen conifers, such as spruce and Douglas fir, and broadleaved trees casting a heavy shade such as beech and hornbeam, are not suited to the provision of direct overhead cover with complete canopy. Only when the crop has been opened out considerably are conditions sufficiently good for the growth of seedlings. Even with trees casting a light shade some break in the canopy is necessary if seedlings, particularly those of their own kind, are to grow satisfactorily. Another factor of importance is the susceptibility of the shelter itself to frost injury. When a series of severe frosts occurs, as in May 1935, a susceptible species such as oak, may have its leaves so shrivelled that the shelter given is appreciably reduced.

The temperature of the air within a wood depends on a number of things. During the day it is lower than that in a similar position in the open, owing to the shade of the trees. At night, it is warmer especially when the trees, if deciduous, are in leaf and the canopy complete. This is due partly to the protection given by the crowns from loss of heat by radiation and partly to the protective effect of woodland against movement of the air within it. The air within a wood thus remains warmer and often circulates less than the air outside it at the same level. The more complete the canopy, not only in the crowns above but also in the lateral branches of the trees, the more does woodland maintain its own special and protected climate.

Side Shelter.

(*a*) *Coppice Woodland.*—Tall coppice may be sufficiently high to provide overhead shelter, but not uncommonly this type of woodland is so low that it can be used only for side shelter. There are two main ways in which such shelter can be treated. It can be left in clumps, and the new crop planted between these, or strip fellings can be made and the new crop planted in the cleared strips. No temperatures are available to give any indication as to the effectiveness of this sort of shelter, but those given in Table XXXIX (page 96), which refer to the shelter given by small uncoppiced trees, illustrate very similar conditions. The thermometers at Stations 1 to 4 were set among trees 4 to 15 feet high. Those surrounding Stations 1 and 3 were mostly Douglas fir and provided shelter which was much closer than is usually left in planting and was in part evergreen. Station 1 had some overhead shelter but 3 had only side shelter. Station 2 was on the edge of a small open space and just beneath the outer edge of a beech about twelve feet high. Station 4 was in the middle of this space, the nearest trees being some beech three yards away and four feet in height. Station 5 was situated under oak high forest with complete canopy. Using No. 5 as a standard, a comparison of the differences between the average temperatures at this point and at the other stations gives some indication of the relative degrees of exposure.

In March, when the deciduous trees were bare there was no difference between Stations 1, 2 and 3, but all were on the average 1·8° F. warmer than No. 4, the fully exposed Station. In May, when the leaves were developing, No. 3 gave lower temperatures than Nos. 1 and 2 while No. 4 was nearly a degree and a half colder than No. 3. In June and July, when the leaves were fully out the differences were still greater. Observations showed that the protection given was not sufficient to save small beech trees during the severe frost of 21st May, 1931 (*see* Table XXXIX) when plants survived only at Stations 1 and 5 and at the latter they were severely injured. Moreover, the thermometers at Stations 1, 2 and 3 were set much closer to the shelter than it is possible to plant small trees with any hope of satisfactory growth. Station 4 shows that quite a short distance away from low side shelter no appreciable protection is given. The figures in Table XLI (page 100) show similarly that in gaps in a young plantation the protection given is of comparatively little value.

Eight reports were received which mentioned side shelter from coppice. In five cases the shelter afforded no protection, one report saying that the sheltered plants were worse damaged than the others; in three cases the shelter was apparently effective, but it is to be noted that all were in areas subject to some of the less severe temperatures, and where vegetation was somewhat backward. It is concluded that in practice low side shelter of the type under discussion is useless against any but the lightest frosts.

(*b*) *High Forest.*—The value of the side shelter afforded by high forest is well known to foresters, and several strip regeneration systems have been devised to make use of the favourable conditions provided[45]. In a recent paper[24] on a late frost in spruce forests in Latvia some interesting figures are given concerning the effect on shelter of the width of the felling strip; the height of the standing high forest is not given. With a 30–40 metre wide clear-felled strip small spruce up to three years only received but little and unimportant damage; when the cleared strip was 50–60 metres wide 29 per cent. of the leaders of the spruce in the middle were killed, the severity of the damage gradually falling off as the edge of the forest was approached. When the felled area was 100 metres or wider the percentage of leaders killed rose to 38–69.

TABLE XXXIX.

Temperatures in 1931 in Horselawn, Forest of Dean.

	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.	No. 9.
	°F.	°F.	°F.	°F.	°F.	°F.	°F.	°F.	°F.
Average Temperatures for :—									
Ten March frosts	20·3	20·3	20·3	18·5	22·6	20·7	18·0	18·2	18·1
Seventeen May frosts	29·5	29·2	27·9	26·5	32·0	28·8	27·0	26·3	26·6
Ten June and July frosts	35·5	37·2	33·8	31·4	38·2	35·7	33·2	31·8	29·8
Average differences between No. 2 and the other thermometers :–									
March	2·3	2·3	2·3	4·1		1·9	4·6	4·4	4·5
May	2·5	2·8	4·1	5·5		3·2	5·0	5·7	5·4
June and July ..	2·7	1·0	4·4	6·8		2·5	5·0	6·4	8·4
Greatest difference between No. 2 and the other thermometers :–									
March	6·0	3·5	5·8	8·2		3·5	9·0	9·0	8·0
May	5·0	9·0	7·5	10·0		7·0	8·0	10·0	11·0
June and July ..	5·2	5·2	6·4	10·1		4·3	7·5	7·7	10·1
Temperatures 21st May, 1931 ..	23·0	18·0	21·5	17·0	27·0	22·0	21·0	17·0	16·0

No. 1. In thick shelter 4–15 ft. high, mostly Douglas fir, but some birch, with slight overhead shelter.
No. 2. as No. 1.
No. 3. As No. 1, but clear overhead.
No. 4. In an open space near No. 2.
No. 5. Over bare forest floor, complete shelter.
No. 6. Uncleared space 18 ft. from high forest to S.E., shelter mostly small beech 4–8 ft. high, but some from high forest.
No. 7. Cleared space 24 ft. from high forest to S.E.
No. 8. Cleared space 75 ft. from high forest to S.E.
No. 9. Naturally open space about 150 ft. from high forest to S.E.

Rebel[38] records similar observations made in frosty flats in the region of Munich and Geiger[18] working in the same places was able to confirm them. They found that the effect of side shelter from a birch stand 15 metres high could be traced for 12 metres out from its edge.

Observations were taken during 1931 in a frosty area known as the Horselawn in the Forest of Dean. The data are set out in columns 5 to 9 in Table XXXIX. The high forest was oak about 60 feet in height.

Station 5, situated several yards within the high forest was appreciably warmer than the other four, but the difference was least in March and, on the whole, greatest in June-July. Of the four out-stations No. 6, which was situated nearest the high forest, was the warmest during each of the three periods. The very appreciable difference between this station and No. 7, which is only two yards farther out from the high forest, may be partly due to this difference in distance from the edge of the shelter but is principally to be accounted for by the fact that No. 6 had overhead shelter from small beech trees. The three Stations 7, 8 and 9 were in line with each other and fully exposed to the sky above. The figures show that neither in March nor in May was there any appreciable difference between them, but in June–July when the oak were in full leaf, Station 7 was 1·4° and 3·4° warmer than Stations 8 and 9 respectively.

After the May frosts, 1935, a few cases were observed in which side shelter by evergreen conifers appeared to have been efficacious. There were, however, marked instances in which side shelter from deciduous high forest, usually pure oak, completely failed. It is doubtful whether such shelter ever gives effective protection against a really severe May frost. In the Horselawn, for example, side shelter signally failed to protect small beech from the very severe frost which occurred on 21st May, 1931, the figures for which are given in Table XXXIX. In the reports received on the effects of the May frosts, 1935, eleven statements were made as to the effect of side shelter from high forest, usually consisting of deciduous trees. In six cases the shelter was claimed to be effective and in five to be ineffective. It is probable that the shelter was effective in those cases where the frost was comparatively slight, or where the plants protected were backward and so comparatively hardy.

The explanation of the frost protection given by high side shelter is fairly simple though as usual more than one factor has to be taken into account. In the first place a site at the edge of tall forest is partly protected from loss of heat by radiation, the trees shutting off part of the sky. Secondly there will be some influence of the warmer air inside the stand, while a third factor may be the reduced size and density of the herbage close to the tall trees as compared with farther out in the open clearing. Side shelter by high forest may thus be expected to offer protection in those places where very low temperatures do not usually occur during spring, and especially where the sheltering trees are evergreen, or if deciduous, happen to be in full leaf. In frost hollows, however, the amount of protection given is not likely to be effective.

Overhead Shelter.—Many trees regenerate best under some degree of overhead shelter. This is not merely a matter of the fall of the seed, but is also related to soil and climatic conditions. Under shelter, climate is less extreme than in the open. The young plant and the soil in which it grows are protected from the sun in the daytime and at night from the extreme severity of hard frosts. On the other hand the shade may be too great, *e.g.*, the shelter provided by the high forest at Station 5, the Horselawn, in Table XXXIX effectively protected beech but was too dense for the trees' satisfactory further growth. On frosty nights the temperature under this dense shelter was, on the average, higher than that in the adjacent open places (Stations 4, 8 and 9) by about 4·5° F. in March, 5·5° F. in May and 6·5–8·5° F. in June and July. The greatest shelter was given, of course, when the trees were in foliage and, as the figures giving the greatest differences in temperature indicate, may amount to as much as 11·0° F. During the severe frost of 21st May, 1931, when this difference in temperature occurred, the beech directly under the high forest alone escaped injury, practically all the others being killed. Most situations are not subject to such severe and frequent frosting as the Horselawn, which is a notorious frost hollow in a district where there are many frosty places. Nevertheless it is well to bear in mind that when really severe May frosts occur, as in May 1935, it requires a really dense overhead cover to protect tender plants from injury.

Some data on the shelter afforded by lighter overhead cover than dense oak high forest are given in Tables XL and XLI. The temperatures were taken with unscreened terrestrial radiation thermometers on three adjacent sites to the N.W. of Olley's Farm near Thetford. The thermometer stations were 250 feet apart, on level ground, at an elevation of 250 feet above sea-level. The soil is sandy. Site A was in the open, the ground being covered with dense *Festuca* grass with a sparse admixture of bracken. Station B was inside a shelter belt consisting of birch, 30–40 feet high and 12–18 feet apart, mixed in places with Norway spruce 10–35 feet high (Plate VI, figs. 1 and 2). This station was in a particularly open section of the shelter belt where there were very few spruce and the birch did not form a complete canopy. Station C was in a grass-covered gap, 9 feet square, in a plantation of Scots pine, 4 to 7 feet high.

The figures in the two tables show that at this place, which is one in which cold air stagnates but not one into which it flows, a high birch canopy may give very appreciable protection against frost injury, whether the trees are in leaf or not. The greatest effect is seen at 2 inches above the ground, but even at 3 feet the temperature differences are considerable. At both heights the differences are greatest when birch is in full leaf.

A comparison of the thermometer readings at ground level and at 3 feet above ground reveals the interesting fact that there was often a marked temperature gradient in the open, the ground level temperatures being usually much lower than those at 3 feet. Under the birch on the other hand there was no great difference between the thermometer readings at the two levels.

TABLE XL.

February, 1936.	Minimum Temperatures at 2 in. above Ground Level at Stations		
	A. In the Open.	C. Among young Pine.	B. Among Birch.
	°F.	°F.	°F.
Feb. 21	18	23	30
,, 22	12	15	25
,, 23	35	36	36
,, 24	27	29	31
,, 25	33	34	34
,, 26	24	25	29
,, 27	34	35	35
,, 28	14	19	36
Average ..	25	27	32

That the state of affairs indicated here is not exceptional is shown by Fig. V. This diagram is taken from a paper by Umann [46]. It

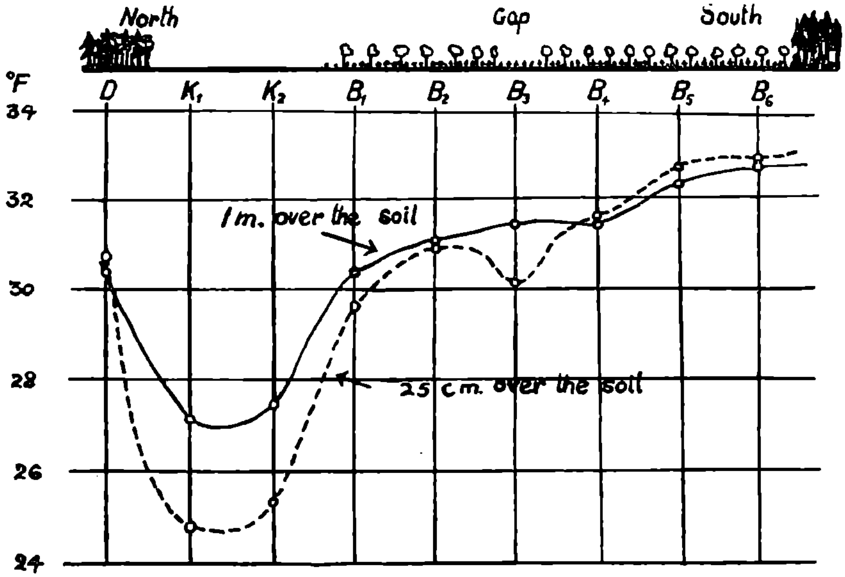


FIG. V.—Average minimum temperatures over a frosty flat in Bavaria. (*After Umann.*)

TABLE XLI.

Stage of Flushing.	Minimum Temperature in				Type of Weather.
	Station A Open.		Station B Among Birch.		
	2 in. above Ground.	3 ft. above Ground.	2 in. above Ground.	3 ft. above Ground.	
Birch buds not yet flushed.	°F.	°F.	°F.	°F.	
1936 April 6 ..	30	34	35	35	Cloudy, very slight N.W. wind.
„ 7	20	27	27	29	Some clouds, very slight N.E. wind till about 3 a.m.
„ 8	25	30	31	33	Some clouds, very slight N.E. wind.
Buds flushing and leaves expanding.					
1936. April 18	24	26	25	26	Cloudy, slight N.W. wind all night.
„ 19	19	28	28	29	A few clouds, mainly still.
„ 20	16	27	26	29	Cloudy, some sleet, slight N.W. wind till sunrise.
„ 21 ..	12	21	22	24	Almost clear, still air.
„ 23 ..	12	20	21	23	Clear and still air.
„ 24 ..	37	38	38	38	Overcast to cloudy, slight N.W. wind.
Leaves fully expanded.					
1936. May 14 ..	29	38	41	41	Few clouds, mainly still air.
„ 15	33	39	43	43	Few clouds, slight wind, still near sunrise.
„ 19	41	42	48	48	Few clouds, but moderate N.E. wind.
„ 24 ..	22	29	34	34	Some clouds, but mainly still air.
„ 29 ..	16	27	32	33	A little cloud, but mainly still air.
June 1	24	29	35	35	A little cloud, but mainly still air.
Average ..	24	30	32	33	

gives the average temperatures of 11 frosty nights, from 6th May to 27th May, 1927, in a frost flat in Bavaria. The temperatures were taken under cover of birch underplanted with Norway spruce, and in the open. On either side of the area investigated were older spruce stands. As at Olley's the temperature gradient is much less steep and the temperatures are higher under cover than in the open. The warmest stations, B5 and B6, are under the influence of the high forest of spruce and benefit from side, as well as overhead shelter.

These examples show that a cover under which Norway spruce can survive satisfactorily can give useful shelter. Any large break in the canopy, however, may let in the frost, *e.g.*, the gap shown in Fig. V.

Overhead shelter is most effective when most complete, and where extensive is more likely to give shelter than where it occurs in small isolated patches. Thus, for example, the isolated trees shown in Plate VII, fig. 1 gave no effective shelter against the frosts of May 1935 whereas the adjacent coppice of which they originally formed part did so perfectly. On the other hand the shelter given by the coppice was too dense for satisfactory growth. In a more favourable situation, a comparatively light canopy of ash coppice, shown in Plate VIII, fig. 1 completely protected beech beneath it, those outside being injured.

In the more favourable situations useful protection can also be given by broadleaved scrub (Plate VIII, fig. 2), which in many of the Commission's forests has been girdled and left as cover for conifers planted beneath it. Such shelter was reported to have been effective in May 1935 in 40 out of 58 reports.

While, therefore, too much must not be expected of overhead cover, it is plain that it can be of great silvicultural value in creating a climate specially suited to the growth of small, tender trees.

Mixture of frost-hardy and frost-tender Species.—It is a common silvicultural practice to plant frost-tender species such as beech, oak, or Douglas fir with frost-hardy, or quick-growing trees (so-called nurses) such as Scots pine, European larch, or birch. Observations show that the nurse species have little or no effect until they are tall enough for their side branches partly to interlace and form cover over the tender plants below.

An example was seen in Alice Holt Forest where oak 3–5 feet high was growing between Norway spruce nurses, 6–10 feet high, there being alternate lines of each species. They were planted in 1927 in strips rather over 30 yards wide, cut through oak high forest. In spite of the presence of close, low side shelter of Norway spruce, and high side shelter from the old trees, the small oak were badly frosted in 1935. It should be observed that the spruce branches were still a long way from meeting and the layer of cold air was very deep.

Advance Crop of frost-hardy Species.—In some situations subject to late frosts it may be possible by establishing an advance crop of a frost-hardy species later to introduce the trees which are desired for the main crop. Birch or alder is often selected for the advance crop and planted fairly widely apart, *e.g.*, at 7 to 9 feet. The frost-tender species can be planted when these nurse trees are beginning to form canopy.

Shelter in Nurseries.

As a result of the frosts in May 1935, very considerable losses were suffered in nurseries. These were due not only to injury, which resulted in some cases in an inferior or useless type of tree being produced, but also from the necessity of keeping many of the plants in the nursery for a further season in order that they might again become suitable for planting out. It is clear, therefore, that the protection of frost-tender trees in the nursery may be a matter of considerable importance.

Shelter may be given in several ways. The nursery may be surrounded by high trees from which it will receive side shelter. Three reports were received of shelter of this type and all were favourable; they came, however, from places where the frost appears not to have been very severe. In the one case Scots pine 30 feet high were reported to have protected a bed of Japanese larch for a distance of 12 yards out; in another, a surround of broadleaved trees and conifers 50 to 70 feet high is reported to have had a good effect. Protection of this kind is useful but on occasion it may prove dangerous in that an unduly shut-in place may sometimes suffer more seriously from frost than an exposed one, owing to the restriction in the movement of air.

The hedges which not infrequently divide nurseries may also give a certain amount of side shelter. Thus a 10-foot beech hedge was reported to have sheltered Sitka spruce for 8 yards out. Five reports were received on such hedges and in three cases effective protection was said to have been given, but in the other two it was not so. It is difficult to say to what extent the ordinary 5- to 8-foot high nursery hedge gives effective side shelter from loss of heat by radiation, but the protection offered cannot extend very far. It is probable, therefore, that in the above cases where such shelter proved useful some other factor, such as protection from cold and freezing winds, may have come in.

The form of protection most used in practice is the low direct overhead shelter of seedbeds such as is provided by laths or branches. Reports show that wherever lath sheltering was used the amount of damage suffered was lessened and in some cases very effective shelter was provided. Birch branches and other brushwood have also been reported on as giving effective protection. In 1933 temperatures were taken with unscreened terrestrial radiation thermometers, placed about 5 cm. above the ground, both under lath sheltering and in the open. The amount of protection given on frosty nights in March and April varied from about 1·5° to 2·5° F., the maximum recorded being 5·1°. Papajoannou[32] carried out some experiments with various types of low shelter including laths. In his case the laths were set at 8 inches above the soil, whereas in ours they were at 12 inches. On the average he found that the amount of protection given was 2·9° F., a figure which agrees very well with the limits given above, especially when it is remembered that the shelter was nearer the soil than was the case in our experiment. Papajoannou also gives figures for the shelter provided by branches of evergreen conifers such as spruce and pine and by straw matting and cloth covers. The branches had no advantage over lath sheltering, are much more difficult to handle and need more frequent renewal. The matting and cloth gave more shelter but were much more costly and affected the plants adversely when it was necessary to leave them on in daytime. On the whole, it would seem that lath sheltering is the best and most convenient form of protection for nursery seedbeds.

An obvious alternative for the general protection of nurseries during late frosts is the use of oil heaters such as have been found satisfactory in the protection of orchards from frost damage. There is no experience of these in forestry and relatively little in fruit-growing in Britain.

Topography and Shelter.

The topographical character of a locality often seriously affects the problem of providing shelter. There are two main complicating factors; one is the drainage of cold air owing to the unevenness of the land; the other is the effect of shelter on the movement of air. To some extent the two are interrelated. It has been seen that the colder and heavier air, which lies over the ground on clear, still nights, drains down hill filling hollows and valleys. A forest is rarely on flat ground and accordingly on nights when severe ground frosts occur there will always be movement of cold air from higher places to lower ones, unless there is some obstacle in the way. To what extent does shelter provide such an obstacle? Many opinions have been expressed with regard to this but few measurements made, and accordingly it is possible here to give only general indications as to what probably happens.

The first point to consider is whether tree canopy offers any marked restriction to the movement of air. If the canopy is complete, loss of heat by radiation will take place on its surface and not from any plant standing beneath, or from the ground. Accordingly as nightfall comes on, the coldest and heaviest air in the ground air zone will be generated at the surface of the crowns. The temperatures taken by Geiger ([19], page 158) in a 50-ft. high pine wood show that with the conditions under discussion the air over the ground is always colder than that immediately over the crowns of the trees, the cold air sinking to the ground.

Evidence that the canopy tends to restrict circulation between the air above it and that beneath it is provided by the observation not uncommonly made that an obstacle running across a slope dams the cold air moving down to the valley, thus creating a frost pocket. It is not necessary for the obstacle to be something solid, such as a wall or earth dyke: a thick hedge, or a belt of trees well branched right to the ground on the side facing up the slope, is quite sufficient. On the other hand if the lower part of the trunks in a belt of trees is bare of branches, air will move through comparatively easily.

Some further evidence in this matter is provided by observations made in a narrow belt of beech which stands on either side of the road which runs along the bottom of Turville valley (Map 4, Point C, page 117). Parts of this belt of trees were very dense with a complete and thick canopy; elsewhere it had been thinned out and the canopy was much broken. The outer trees on both sides branch to the ground. Where the canopy was dense and unbroken the leaves on the inside of the crowns remained practically unhurt after the May frosts, 1935, as also did any on small trees surviving beneath the dense shade; the outside leaves were killed. On the other hand, where the canopy was broken none of the leaves escaped damage. Similar observations in valleys have been made in India [(30)].

It would appear that in this case, where the valley was filled with freezing air to a greater height than the trees, there must have been some local restriction of circulation, the dense canopy acting to some extent like the walls of a greenhouse.

It is also a matter of some importance to consider what happens when the shelter available is quite low, but is situated in a valley where the cold air may rise up and entirely cover it. An interesting case illustrative of this was observed near Chiddingfold in Sussex (Map 6, Point A, page 119). On this site oak woodland has been cleared and planted up with Sitka spruce. In 1935 the spruce were about 7 to 10 feet high, and in many places were embedded in a dense growth of coppice which was about 6 feet in height. The cold air in this valley rose to a greater height than the tops of the surrounding old oak, all the leaves on which were killed. Wherever the spruce were exposed out of the shelter of the coppice they were very severely frosted, so much so indeed that catastrophic damage very nearly occurred. The damage ceased to be very marked, however, about 6 inches beneath the coppice canopy. Obviously in this case the dense coppice had exercised a very marked sheltering effect on the parts of the trees embedded in it, and this in spite of its own leaves being killed, and of the air above its canopy having a sufficiently low temperature to damage severely or kill all the leaves on tall oak trees. The shelter was so dense, however, that the spruce branches included in it were being suppressed. Here, as so often, we suffer very much from lack of temperature data, but the evidence provided by the frost damage seems to show conclusively that the plant temperature, and probably the air temperature within the coppice, were appreciably higher than those outside it.

The general conclusion is that where a woodland is so situated that cold air flowing down from higher parts may rise higher than its canopy, be this high or low, protection from frost damage becomes much more difficult than on the warmer higher slopes, or even flat hilltops where, although the colder air is stagnant, it does not lie so deep. The very low temperature of the air collecting in the valley may be sufficient in itself to cause damage, even though the tender plants are completely protected from radiating to the open sky. Only when a complete, and perhaps fairly dense canopy is available as cover does there appear to be any hope, in such situations, of providing efficient shelter against severe frosts.

Aspect and Shelter.

Aspect is of special importance in connection with side shelter, as all will realise who have studied the various " strip " systems of natural regeneration. A useful summary on this matter is given by Troup ([45], pp. 89–94) in connection with the strip system known as " Wagner's Blendersaumschlag ". The main factors concerned are frost, sun and wind; whether shelter from or exposure to these is advantageous largely depends on climate. One of the principal problems, so far as frost damage is concerned, is whether or not plants should be sheltered from the morning sun. It is always claimed that the rapid thawing, consequent on lack of such shelter, results in increased damage. If this matter is tested experimentally by freezing plants in a refrigerator and then exposing them to rapid thawing in various ways, evidence is obtained in confirmation of this, but the differences between rapidly and slowly thawed plants are usually very slight. Observations in the field with regard to this are often unreliable because no note has been taken of the state of development of the plants. In the northern hemisphere strip fellings are often made facing north to cut off the morning sun, but on this aspect plants tend to flush later. The apparent escape from frost injury of plants on north aspects may be as much due to delayed development as to any protection from the morning sun.

Wind and Shelter.

There is no doubt that shelter, by checking the flow of air, often increases the liability to frost damage. On the other hand, a number of reports has been received in which it has been claimed that protection from wind has resulted in less damage. At least two factors are involved. First, as already mentioned, wind mixes up the cold air generated over the earth's surface with the warmer air higher up and thus prevents the temperature from falling as low as it would if calm conditions prevailed. Secondly, wind increases the rate of evaporation from any moist surface with a consequent lowering of the temperature. Geiger ([19], p. 81) gives figures supporting this statement. During the May frosts of 1935, both rain and snow fell in many parts of the country, and sometimes the vegetation was moist at nightfall; conditions were therefore right for this lowering of the temperature near the ground to take place. Hence possibly some of the more curious anomalies of the frost.

Silvicultural Considerations.

Shelter and Regeneration.—The above discussion on the effects of various types of shelter in reducing the climatic extremes which occur immediately over the soil, suffices to show that measures carried out to prevent frost damage to young trees must inevitably take their place as fundamental silvicultural operations. The importance of this aspect of silviculture has, perhaps, been somewhat overlooked in Britain. The cause of this is probably that large-scale operations in forestry have been mainly concerned with the planting of clear-felled areas or of bare land. It is to be noted, however, that in the case of the beech woods on the chalk downs, which provide the only example of a frost-tender species long established and grown to some extent on lines which approach efficient modern management, regeneration is obtained naturally under shelter. When the afforestation of open downland is attempted by directly planting beech, difficulties are met with which largely arise owing to the extreme conditions of the micro-climate within which the small newly planted trees live.

The natural succession in the colonisation of chalk downland follows the sequence, broadleaved scrub, ash, oak, beech, beech colonising the area last and finally becoming dominant. The hardy trees of British woodland, such as hawthorn, blackthorn, birch, aspen, alder, in their respective ecological spheres are the forerunners of more sensitive species such as oak, ash and beech, which eventually dominate them,

While, in the practice of economic forestry, it may not be possible to follow the natural sequence of colonisation, this should never be forgotten. This is true even of the exotic conifers upon which economic forestry in Britain so largely depends; with the exception of the larches and pines, the more important species of conifers are more or less shade-bearing and naturally suited to regeneration under shelter. The difficulties experienced in their use in afforestation are due, to no small extent, to the fact that they must of necessity be planted in the open. Whatever may be convenient economically, from the biological standpoint the conclusion seems to be inevitable that shelter is usually desirable for the growth of small trees of such species.

Choice of Species.—Frost is by no means the least of the many factors which the forester has to bear in mind when considering the choice of species. In some localities liability to late frosts may dictate the choice of a frost-hardy tree however suitable the soil may be for other and more profitable species. Many of the difficulties should, however, disappear once a crop has been established and use can be made of the shelter provided by the pioneer crop.

Planting of cleared Areas and Frost Injury.—The planting of cleared areas is often an unavoidable or convenient method of regenerating the forest, but it entails a number of difficulties affecting the growth of the young trees and these, directly or indirectly, affect the liability of plants to frost injury. Firstly, the mere disturbance of the root in transplanting causes a check to the growth of the plant, even when the greatest care is taken. Secondly, in replanting, the root system is often badly distributed and this frequently gives a further set-back to the tree. Thirdly, planting is commonly done into a soil which has deteriorated, so far as the growth of trees is concerned, owing to grazing or to lying waste as heath or moorland, or, perhaps, owing to clear felling. Clear felling may not always be a disadvantage silviculturally, but undoubtedly it is so on some soils, *e.g.*, clays. Fourthly, growth may be made difficult by a dense cover of weeds, and lastly the young trees are exposed to the most extreme climatic conditions which can occur on the site.

The effect of these considerations is that the young trees grow slowly while root regeneration is taking place and weed growth is being suppressed. The result is that the crown of the tree, or more particularly its leader, remains within the cold and dangerous lower zone of the air longer than would be the case if better conditions for root regeneration and growth existed. Hence the difficulty of establishing many of our trees in frosty localities.

Prevention of Frost Injury.

(*i*) *By Soil Cultivation.*—Cultivation of the soil can have two effects. It can directly stimulate the growth of the tree by making food substances more abundantly available and it can affect the temperature over the soil. Bare or well-drained soil is warmer during the day, and gives off more heat at night by conduction to the air immediately overlying it. The stimulation of growth results in the trees growing through the dangerous zone more quickly than would otherwise be the case.

(*ii*) *By careful Planting and Choice of Plants.*—A similar argument applies to the type of plant used and the method of planting. The main aim must be the rapid regeneration of the root system. The type of plant chosen should be that which can best be handled in transport and planting. If a large plant can be handled successfully it is usually better than a small one in that its head is more likely to be above the point where the lowest temperatures occur, and often there is more chance of its recovery after injury. In a frosty area, the cheapest method of establishment is usually that which gives the trees the best chance of recovery from planting and of making vigorous growth. The cost to be considered should, in fact, be that of satisfactory establishment and not merely of planting.

(*iii*) *By Provision of Shelter.*—One of the chief lessons to be drawn from the observations recorded in this Bulletin is the value of high shelter as a protection against late frosts. Tall worthless scrub or inferior trees left after a felling has been made, are often cut and cleared at a loss in order to have a bare area ready for straightforward planting. The ringing or thinning-out of scrub and the retention of existing trees will often provide much better conditions for the new crop than if the ground is completely cleared.

Where no previous tree crop exists the method of an advance crop of a frost-hardy species or the use of hardy trees as nurses will often enable the desired species to be established even in situations which are distinctly liable to late frosts.

CONCLUSIONS.

Frost is one of the more important climatic factors affecting the regeneration of the forest in a temperate climate. A study of the various silvicultural systems employed in forestry shows that their efficacy depends in part at least on the protection from frost given by the mother trees to the regeneration below. In Britain, however, we are engaged on a big scheme of afforestation in which shelter is, of necessity, usually lacking, and yet species must be used which are bound to suffer from frost, given certain meterological conditions. It is these conditions, as deduced partly from theory and partly from the evidence provided by the phenomenal late frosts of 1935, that this Bulletin attempts to describe.

The meteorological aspect of the problem concerns primarily the climate of the ground air zone. Loss of heat by radiation from the earth's surface on still clear nights, the pooling of cold air in hollows or valleys, and the downward flow of cold currents of air over the surface of sloping ground are the chief factors in regard to late frosts. Except on low ground the depth of freezing air is usually quite small, often not more than two to three feet and seldom exceeding ten feet, hence serious damage is generally confined to young trees and shrubs.

The extensive frosts of May 1935 provided an exceptional amount of data on the question of frost damage. It appears that with few exceptions all large trees recovered satisfactorily from damage, severe though this may have been (Plate IV, fig. 2). Small trees and shrubs, on the other hand, suffered much more serious injury in numerous but restricted localities. The topographical features of the land are shown to play an all-important part in relation to the incidence of frost; the examples given in Appendix II illustrate the extremely varied conditions under which frost damage occurred.

The several forms which frost damage may take are described, the most serious being such extensive injury to the cambium of the young stem as to cause the death of the plant; next in order of severity comes the killing of the leading shoot resulting in loss of height, crooked stems, or forked leaders. If late frosts were very exceptional this might not have any great significance; unfortunately there are many localities subject almost annually to late frosts and it is the cumulative effect of damage occurring in successive years or at frequent intervals which is so serious.

It is difficult to form even a rough estimate as to the total area of forest land seriously affected by spring frosts. The flat sandy heaths of Norfolk and Suffolk, known as the Breckland, form perhaps the most extensive tract of country subject to recurrent late frosts, but there are many other localities, more especially valley bottoms and the steep slopes of narrow valleys, where frosts are liable to damage all but the hardiest species of young trees.

Apart from climatic phenomena and topographical features the stage development of the vegetation plays an important part in determining both the type and extent of frost damage. If, as is often the case with conifers, the buds of the leading shoot are not flushed at the time of the frost, damage may be confined to the side branches and the leader continues to grow unharmed.

A considerable amount of space has been devoted to the question of shelter. In very frosty localities the forester must either content himself with a frost-hardy species such as Scots pine or he must introduce some form of shelter. The 1935 frosts demonstrated clearly that of all types of shelter much the most effective is that afforded by a high canopy with the branches almost interlacing above the young plants. Other types of cover may be helpful against slight frosts but will not keep out frosts of any real intensity.

The problem presented by spring frosts goes farther than the mere observation of frost damage or the attempt to avert that damage by the provision of some form of shelter. Frequently serious frost damage occurs in places where the soil conditions are to some extent unfavourable to tree growth. When such conditions exist the trees recover more slowly and take longer to get above the usual level of cold air than would otherwise be the case. Although permanent improvement of the soil may be outside the scope of the forester, various measures, including cultivation, manuring, use of strong plants, and adequate drainage may be taken to improve conditions, at least temporarily, and so give the plants much needed assistance.

One further aspect of the problem which may be mentioned is the relationship between frost injury and disease. Frost injury is in itself a form of disease but may also make possible the development of parasitic disease either by providing injuries through which parasites can enter, or by so reducing the vigour of trees that they become a relatively easy prey to such organisms. A discussion on this question will be found in a previous paper of the authors[(13)].

The varying susceptibility to frost of our trees was well illustrated in 1935 and a summary of the information collected has been presented. The question is complicated by the period at which frost occurs and either earlier or later frosts would probably have shown a somewhat different order of susceptibility. The record stands, however, and can be amended in the light of later experience.

While this Bulletin is in the main concerned with trees of economic importance in forestry, the lists of species observed or reported on include many ornamental trees and shrubs. It is hoped that these lists will be of interest to arboriculturists and gardeners whose trees suffered damage in 1935 and in some degree may be of guidance in future planting. They can also serve as a foundation upon which a record of personal observations can be made as to the hardiness of the many beautiful trees and shrubs grown in this country.

APPENDIX I.

The late Frosts in 1935 and the Weather Conditions associated with Them.

Before dealing with the mid-May frosts, which were those causing the severe and widespread damage, it will be best to pass briefly in review the other frosts which occurred in May and early June, 1935. For the sake of brevity in mentioning any particular frost, the date given will be that on the morning of which the minimum temperature was read. This is, in actual fact, an accurate expression of the date of the frost, as with late and early frosts the minimum almost invariably occurs in the early morning.

A quite severe frost occurred on 2nd May in the Eastern Counties and in the London district. At several stations in Norfolk and Suffolk the minima recorded equalled, and in one case the temperature was lower than, those in the mid-May frosts, but being nearly a fortnight earlier and the vegetation correspondingly less advanced, comparatively little damage was done. The same frost, which at some stations extended to the 3rd May, was also recorded at places scattered over a wide area, *e.g.*, in Kent, the Forest of Dean and at Oxford, but so far as is known it was a " damaging " frost only in the Eastern Counties. Two stations in the Scottish Highlands and two in Cheshire reported severe frosts on 10th May. Delamere in Cheshire experienced the lowest temperature on 12th May, but the general frost, which will be considered in more detail below, did not set in till 13th May, and extended from then till 22nd May. 24th to 27th May was a period of frost in parts of north-east and east Scotland and, though the temperatures were higher than those of the mid-May frosts, they were reported from one forest area in Morayshire to have done more damage than those of a week before. Again, on 31st May, a frost occurred which gave the lowest temperature of the month at Nairn and was the only damaging late frost at several areas in the Moray Firth region. It was also recorded at Benmore, Argyll, and probably occurred in other Scottish areas.

This period of frost which began on 31st May extended over 1st and 2nd June and became more general, being recorded in Peeblesshire, the county of Durham, Yorkshire, Derbyshire, and Norfolk, as well as in the Moray Firth district. Slight damage by this frost was reported from Thetford, Norfolk, and it is probable that in a few frosty localities it damaged the young shoots on plants that were recovering from the mid-May frosts. On the 8th and 9th June frosts were recorded in the shires of Kirkcudbright and Wigtown, but also near Aberdeen, at Eskdalemuir on the Border, and at Rickmansworth, Herts; the last mentioned, however, lies in a frosty valley. In no case were these June frosts so severe as those in mid-May. In frost hollows and valleys frosts were probably much more frequent throughout the whole period under discussion than has been mentioned. For instance in Horselawn, a shallow frost hollow in the Forest of Dean, where readings of minimum temperatures were taken every other day, only those read on 2nd, 26th, 28th and 30th May, and on 1st June were above freezing point, for the period 1st May to 5th June.

The barometric conditions which were responsible for the mid-May frosts are described by Oddie ([25]). From the 14th to the 18th May pressure was low over Norway, causing a general tendency for northerly polar winds over the British Isles. Disturbances forming in this northerly current and moving south, were responsible for the very variable weather experienced during the period of most severe frost. The state of the weather as regards clouds and precipitation, and to a lesser extent as regards wind, was so variable that it is quite impossible to tell exactly under what meteorological conditions frost took place in any locality which was not in the immediate neighbourhood of a meteorological station. Nor, for a similar reason, is it possible to make any general statement as to the conditions accompanying thawing. The following summary indicates broadly the sequence of events.

On the night of 10th–11th May the wind had become generally north-east, except in the north of Scotland. This wind was associated with a depression over north-east Russia, and an anticyclone over Iceland, but was not of such definitely polar origin as the winds which followed later; it persisted till the 13th. In most parts it was too high to permit of a severe radiation frost developing; in any case the general air temperature had not yet fallen completely from the high level it reached on 6th May.

On the night of the 11th–12th the weather was generally fine to cloudy, with the wind in nearly all areas over 8 m.p.h. In parts of west England, however, the wind fell to below 4 m.p.h., and it must be presumed that a low wind, combined with a locally clear sky, was responsible for the severity of the frost at Delamere in Cheshire.

On the night of the 12th–13th, when frost was more general, the lowest temperatures of the month were registered at several stations in Lancashire, Cheshire, and along the north coast of Wales, as well as at individual stations in mid-Wales, Hampshire, Sussex and west Scotland. The weather was generally fine to cloudy, except in north Scotland where cloud was general. The wind was generally between north-east and north-west except in parts of Scotland, where it changed temporarily into the south. In the south of England the wind fell below 8 m.p.h., in parts of Scotland below 4 m.p.h., and in parts of west England complete calm was experienced. This calm presumably made possible the low temperatures already mentioned. At most stations the dew-point was markedly lower than on the previous night.

The night of the 13th–14th gave the lowest temperature of the month at two stations in the Isle of Wight, one in Dorset and one on the Moray Firth. At a number of stations, chiefly in Hampshire and Dorset, it was bracketed lowest with some other night. The weather was again generally fine to cloudy, but there was a good deal of scattered rain, and it is probable that in the east of England and in the east Midlands there was enough cloud to prevent frost. The wind, while having a northerly tendency over most of the country, backed into the south-west for part of the night in south-east and east England. These winds were associated with a depression over the southern North Sea, and with high pressure areas over the Hebrides and south of Iceland. Again the wind fell below 4 m.p.h. in the area most affected by the frost.

On the nights so far dealt with the frost was not generally very severe. Lancashire, Cheshire, north Wales, the Isle of Wight and Dorset were all areas which escaped comparatively lightly; the only outstanding temperature recorded being a grass minimum of 16° F. at Micheldever in Hampshire on 13th May. On the night of the 14th–15th frosts were much more generally severe. Over the extreme north of England, and in Scotland south of a line drawn from Girvan in Ayrshire to Edinburgh, this night was, almost without exception, the coldest of the month, screen temperatures below 25° F. being quite common. It was also the coldest night of the month at several stations in east and north-west Scotland, and at three on or near the south coast. There was, however, very little frost on this night in east England, in the Midlands, and probably also in south-east England and Wales. In England the wind was still generally north and associated with a depression over west Europe and an anticyclone over the Atlantic. In the north of England the wind backed into the south-west for the night and the next morning, but was actually a continuation of the cold northerly current of air that was now passing south on the western side of the depression that had formed over Norway. In parts of north England and in south Scotland, *i.e.*, in that area lying between the two depressions mentioned above, the wind speed became very low; in fact in parts of south Scotland complete calm was experienced. It fell below 4 m.p.h. locally in the west, where there was severe frost at Manchester and in Cheshire. In the eastern counties cloud and rain effectively prevented frost. Over the rest of the country the weather was fine to cloudy. Once again, therefore, severe frost occurred where the wind speed was sufficiently low to permit of the pooling of cold air, and where there was a sufficient absence of cloud to permit considerable radiation to the upper air.

The night of the 15th–16th was the coldest night of the month in a few scattered areas ranging from the Highlands to south England, and as cold as the 17th at places in Moray and in Orkney. Except in the south-east, where the wind backed temporarily into the south-west and dropped to below 8 m.p.h., there was a fairly steady wind, generally from the north, associated with a low pressure system stretching from Norway to France. The weather was generally cloudy and rain and snow fell in many places, snow particularly in the north. It would seem likely that in most places, on this night, we are not dealing with a radiation frost, but rather that the temperature of the wind was now below freezing point or so near freezing point that very little extra loss of heat was required to produce a frost.

The night of the 16th-17th was the outstanding night of the period and was assumed by many people to be the only one on which an important frost occurred. It will already have been realised that this was far from the case; nevertheless, it was the coldest night of the month in places ranging from Shetland to Guernsey. Complete calm was experienced in parts of south and south-west England, and nearly everywhere but in north Scotland the wind fell below 8 m.p.h., and often below 4 m.p.h. Again the wind backed temporarily into the south-west except in Scotland. These south-west winds were actually a continuation of the cold winds from the north round the south-west end of a secondary depression and did not, therefore, differ much in temperature from the direct northerly current itself. Weather was fine to cloudy, except in the north of Scotland and the Isles where cloud predominated; some rain and snow fell in north England and in Scotland. This night dew-points were on the average lower than on any other night during the frosty period. Some particularly low temperatures were recorded, *e.g.*, grass minimum temperatures of 9° F. and 10°F. at two stations in the Forest of Dean, and a screen minimum of 17° F. at Rickmansworth, Herts. A number of stations had screen minima below 25° F., and a great many registered readings of 26°, 27° and 28° F. There were two large stretches of country in which this frost was predominant. The larger was bounded on the south by a line running from Kent to Somerset, omitting Hampshire and Dorset, and on the north by a line running from Suffolk to the Carnarvon peninsula. The other was the eastern coastal belt in Scotland from Aberdeen south to the Firth of Forth.

During 17th May, a secondary depression, which formed during the night of the 16th-17th near the Isle of Man, passed southwards across Wales and south-west England, bringing snow to all parts but the south coast. By the night of the 17th-18th, however, this secondary had moved away over France, and as Britain lay in the area of light winds between two low pressure areas, there was again a sharp frost. This was the coldest night of the month in places scattered from Cornwall in the south to Argyll in the north, and such places predominated in Cornwall, in Norfolk and in Argyll. The frosts in Cornwall were not very severe, but a grass minimum of 12° F. was registered at Thetford in Norfolk, and one of 16° F. at a station in Argyll. By this night the period of damaging frost had definitely ended in north and east Scotland, where no significantly low temperatures were registered. The wind remained in the north, showing a tendency to be north-east in southern, and north-west in northern, Britain, and was still associated with the depression over Norway and the secondaries that had passed southwards from it. The weather was generally fine to cloudy, but there was scattered rain, particularly in the north. This night was rather exceptional as regards the connection of wind with frost, because in the eastern counties and south-west, the wind failed to fall below 8 m.p.h., whereas in most other parts of the country it fell below that figure in places, and often below 4 m.p.h. The type of injury that occurred in some parts of Norfolk seemed to indicate that in spite of the appreciable wind current a pooling of cold air had taken place.

During the 18th a depression moved south-east from Iceland to the Hebrides and more or less cut off the supply of cold air. Nevertheless it must be remembered that a large bulk of very cold air had come south, and until this was warmed or replaced conditions were likely to remain cold, and this was in fact the case for some days longer. The night of the 18th-19th was the coldest of the month at several stations in Yorkshire, one in Gloucestershire and one in the Isle of Wight. Severe frost was still widespread, a grass minimum of 13° F. being registered at Thetford, Norfolk and one of 15° F. in the Forest of Dean, and it almost certainly extended to most parts of the country except north and north-east Scotland. The wind during this night was generally very light and variable, blowing from all points of the compass except north and north-east at different places. The weather was in the main fine to cloudy, except in the west and south-west where it clouded over in the latter part of the night and rain fell.

By the next night, that of the 19th-20th, frost was becoming much more restricted. It was the coldest night of the month at two stations in north-east England, but most parts of the country except north England and south Scotland escaped frost altogether, and in the areas affected no particularly low temperatures were recorded. The wind over England was still light and variable, but over most of Scotland it had gone back into the north-east and was slightly stronger, but was no longer of such definitely polar origin. Over all parts of the country, except northern England and the Scottish Isles, the weather was cloudy and rain fell : in northern England fine to cloudy conditions prevailed, making a frost in that area possible. This night was marked by a very general rise in dew-point values, which at most stations were over 40° F., whereas for the past seven nights they were nearly always below 40° F. and sometimes below 30° F.

On the night of 21st–22nd May scattered frosts were experienced in various parts of the country including east and north England and south Scotland, but there were not severe. The wind was now generally northerly again and light. The weather was mostly fine to cloudy, but the general air temperature had now risen to a point which precluded severe frosts even though the conditions for radiation were favourable. This night was, however, the coldest of the month at one station near Manchester and bracketed coldest with other nights at several stations in that district, but the temperatures registered were not very low. The wind was now generally in the north-east and stronger, except in Scotland and parts of the west of England where it was still light. The weather was generally fine to cloudy; in the south-east the sky clouded over in the latter part of the night, but in the west it was fine, and this circumstance, combined with the absence of wind, presumably made possible the frost in the Manchester district. There were also frosts this night, but no really low temperatures, in the west Midlands and in north England and south Scotland.

The next night, that of the 22nd-23rd, the frosts were quite over; in most parts of the country the winds were north-east and of moderate strength, and in north Scotland where the winds were light, the sky was cloudy. Conditions were generally not favourable for the development of frost.

APPENDIX II.

Influence of Topography on Severity of Frost.

Aspect, Slope and local Climate.

Some interesting figures regarding the relationship between aspect and slope, and frost damage to orchard trees, as measured by amount of fruit crop, are given by Bane[4]. These were collected in Kent after the May frosts, 1935. Judging the orchards by aspect, the amount of injury occurred in the following order beginning with the least affected :—north, east, south, west. It is to be noted here that the easterly aspects, which were first exposed to the morning sun, suffered less injury than the westerly ones which were sheltered from it. The differences were not, however, very large. The amount of frost damage to the fruit was also estimated in relation to steepness of slope. There was no appreciable difference between gentle and medium slopes, but orchards on steep slopes escaped much more lightly.

Forty-seven of the reports from the Commission's forests mentioned the relationship between aspect and damage. These reports have been classified according to aspect and divided into two classes, those which escaped with little or no damage being separated from the rest. So classified, the reports arrange themselves as follows :—

——	N.W.	N.	N.E.	E.	S.E.	S.	S.W.	W.
Little or no damage..	1	3	2	1	2	7	3	1
Moderate or severe damage	6	6	2	4	1	3	3	2

Grouping separately the northerly and southerly aspects it appears that the northerly aspects suffered more severely but the data are not sufficient for a valid conclusion to be drawn.

The reports from the Commission's forests also commented on the degree of severity of frost damage on hilltops, slopes and in valleys. This information is summarised in the following table.

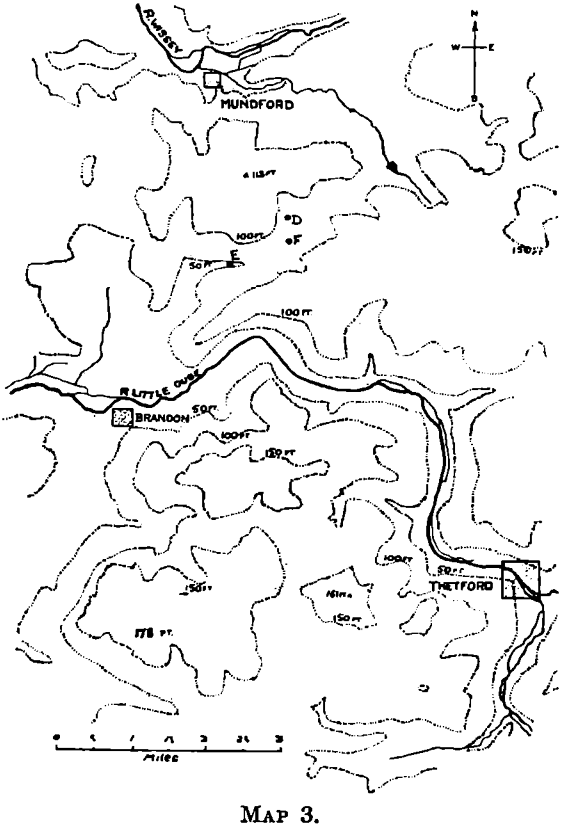
	No Damage.	*Slight Damage.*	*Severe Damage.*
Hilltops	42	11	4
Slopes	9	11	27
Valleys	—	4	93

These results agree with what should happen in theory. There are, however, two possible explanations. On still, clear nights the hilltops are warmer than the valleys and slopes, flat plateaux providing the only exceptions. Hilltops are also more exposed and colder than the lower land and for this reason the trees on them may have been less advanced in growth. It may be taken as certain that both these factors have played their part, but there is not sufficient information available to say what is their relative importance. The table sufficiently demonstrates, however, that slopes and valleys are more dangerous places, as regards frost damage, than hilltops. taking things as a whole.

Type of Topography and Severity of Frost.

In order to make clearer the relationship between topography and severity of frost, the occurrence of frost damage on a number of selected forest areas is discussed below. All the forests referred to have been visited since the May frosts, 1935, with the exception of Cynwyd, N. Wales, which was visited in 1934, for the purpose of investigating frost damage. Altogether they cover a number of topographical types, sufficient, it is hoped, to illustrate the main types of country occurring in this topographically variable island. Owing to lack of the necessary data it has not been possible to give an account of the meteorological conditions in the various places discussed. All that is attempted is to give illustrations showing how severity of frost, as indicated by the amount of damage suffered, varies with the varying topographical types.

The Plain and Plateau.—The essential feature of these types is their flatness. The plain and the plateau or elevated plain, are usually somewhat undulating, but, except where valleys have been excavated, aspect plays an unimportant part in determining the climate of the ground air zone. The best illustration of the plain among the forests in Britain is provided by the large recently afforested grassy heaths of Norfolk and Suffolk, centred round Thetford. Map 3 shows a part of this area. The Little Ouse river crosses the centre of the map, and at the top is seen a part of the upper reaches of the River Wissey. Both of these rivers flow west in the region shown. The river valleys are shallow and flat and the streams moderately sluggish. The steepest slopes are found on the descents into these valleys. Elsewhere all slopes are quite gentle and there are no considerable eminences. There are, on the other hand, many slight hollows, rather shallow valleys and almost flat areas. The soil is sand overlying chalk, the chalk often being quite near the surface and within the rooting depth of trees. After enclosure and before afforestation the vegetation consisted mainly of a thick, moderately coarse turf with bracken and heather occurring abundantly in places : there were few trees except those in the narrow shooting coverts. Before enclosure the large population of rabbits often reduced greatly the height and density of the herbage.



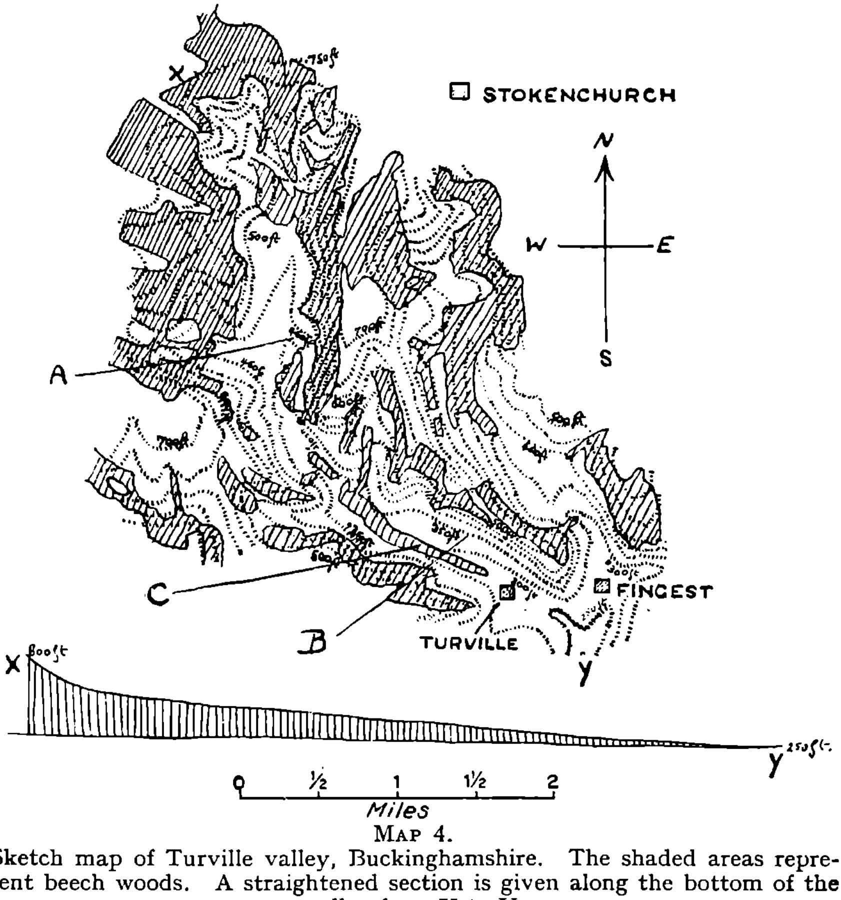
MAP 3.

Sketch map of an afforested part of Breckland on the borders of Norfolk and Suffolk.

This is a district with a dry climate, the result of a low rainfall intensified by sandy well-drained soil. Ground frosts occur not only throughout the spring and autumn, but even in the summer. On still, clear nights the cold air lies like a blanket over the greater part of the area, being especially deep in each slight hollow or valley. In these circumstances frost forms one of the great problems to be considered in attempting afforestation, and provides one of the main reasons for the choice of the hardy pines.

Among the reasons for the severity of the ground frosts are (i) the flatness of the ground which does not permit the heavy cold air to drain away; (ii) the dry, clear air which favours loss of heat from the ground by radiation; (iii) the thick grassy turf which usually covers the soil, and (iv) the dry sandy soil with its comparatively low specific heat and low power of conduction. The turf is one of the most important of these factors. The long, dense grass blades cool rapidly at night, while the turf acts as an insulating layer which effectively prevents the heating of the soil by day and the conduction of heat to the radiating surface by night. The result is that not only are the trees of tender species subject to frequent and usually annual frostings while small, but, owing to drought and other unfavourable conditions for growth, they usually emerge very slowly from the dangerous frost zone. Except in hollows this zone is not deep and, as a rule, the top of a tree which is five to six feet high is out of any real danger.

Some of the best examples of plateau forest are provided by the beech woods situated on the flat tops of the Chiltern Hills (*see* Map 4). The situation

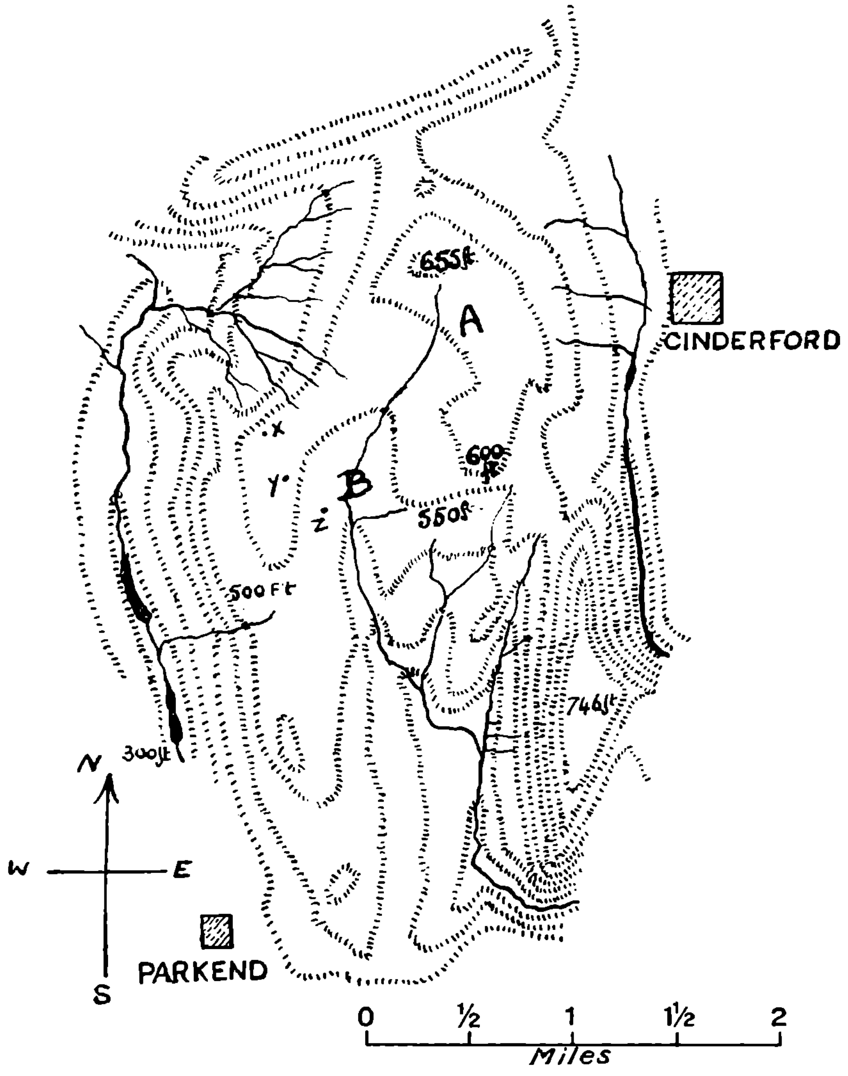


Map 4.

Sketch map of Turville valley, Buckinghamshire. The shaded areas represent beech woods. A straightened section is given along the bottom of the valley from X to Y.

is very similar here to that round Brandon as regards ground frost except that, probably, severe frosts are not so frequent. During the May frosts, 1935, the tall beech on the plateau escaped damage because they stood well above the freezing air, which was never more than ten to twelve feet deep and often much shallower. Any small, tender trees and beech hedges in the open were cut back, however. There is no doubt that some protection is desirable for the successful regeneration of frost-tender trees on these plateaux.

The Forest of Dean is also situated on a plateau through which deep valleys have been cut (*see* Map 5). The central plateau is slightly concave with very poor air drainage and is notorious for damaging spring and autumn frosts. The area from A (in Great Kinsley Inclosure) to B (the Horselawn)

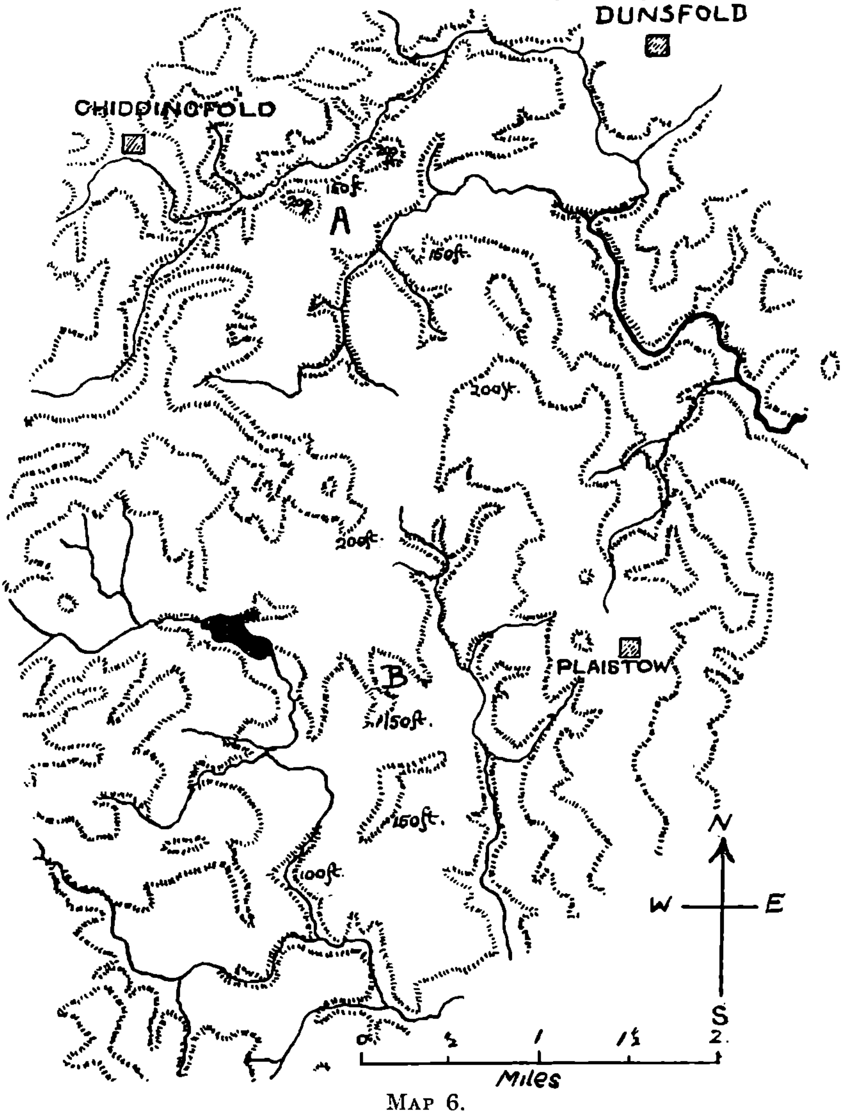


MAP 5.

Sketch map of the centre of the Forest of Dean.

is the part most seriously affected. Not only is the slope of the ground very slight, but the drainage of cold air is hindered by irregularities in contour which are too slight to be shown on the map. Drainage is also further hindered by surrounding high forest. Here, as in the Brandon district, ground frosts occur throughout the summer. On account of the basin-like nature of the locality and the heavy sub-soil, land-drainage is bad and this adds to the difficulties. The edge of the plateau above the steep valley slopes, on the other hand, is fairly free from dangerous frosts.

The broad Valley.—There is not the information available to discuss the liability of broad valleys, such as that of the Thames or Severn, to suffer from severe radiation frosts. Such valleys are, however, not of necessity especially subject to severe spring frosts. When the valley is very broad it forms a



MAP 6.
Sketch map of part of the Weald near Chiddingfold.

plain and conditions arise similar to those discussed in the previous section. Often, however, the temperature conditions in the ground air zone are much influenced by the drainage of cold air down from the surrounding hills (Fig. I, page 18) and the height and steepness of these largely affect the amount of cold air which will drain down into the valley. An example of a broad valley in which very severe frost damage occurred in 1935, and has also occurred on previous occasions, is provided by the Weald in western Surrey and Sussex. This lies between Greensand hills to the north and the south. Near Chiddingfold, where the area shown in Map 6 occurs, the valley is about ten miles wide. The hills rise four to six hundred feet above it both to the north and east; on the south they are somewhat lower. The woodland visited in this area lies in between the villages of Chiddingfold and Plaistow and the points marked A and B are places where very severe frost damage occurred to young Sitka spruce and other conifers established on the site of the previous oak woodland.

The main physical features of the Weald, at this point, consist of low, flat-topped hills and shallow valleys. Aspect is usually of little importance in determining local climate. There is no effective natural drainage for air from this part of the Weald which is entirely surrounded by hills. The rivers draining it rise chiefly to the north and run south, breaking through the South Downs to the sea. The Weald is thus a hill-locked basin from which, during radiation frosts, cold air can drain but slowly.

Frosts are severe in this area, chiefly because it is part of a basin from which the heavy cooler air cannot escape easily. The freezing air often lies deeper than in the open plain or high plateau discussed above, and the problem of the protection of small trees is somewhat more difficult because of this. The difficulty is increased by the relatively unfertile nature of the soil. Frosts which cause severe damage are usually separated by a number of years; *e.g.* the last severely damaging frost at A and B on the map, previous to 1935, occurred in May 1927. If a tree such as Sitka spruce can attain a diameter of three or four inches at the butt it is unlikely to be disastrously damaged by any May frost. Accordingly the sooner it is able to attain this size, the less is the chance of such injury. Fast growth is thus a great advantage in frosty localities, provided it is accompanied by proper ripening of the shoots.

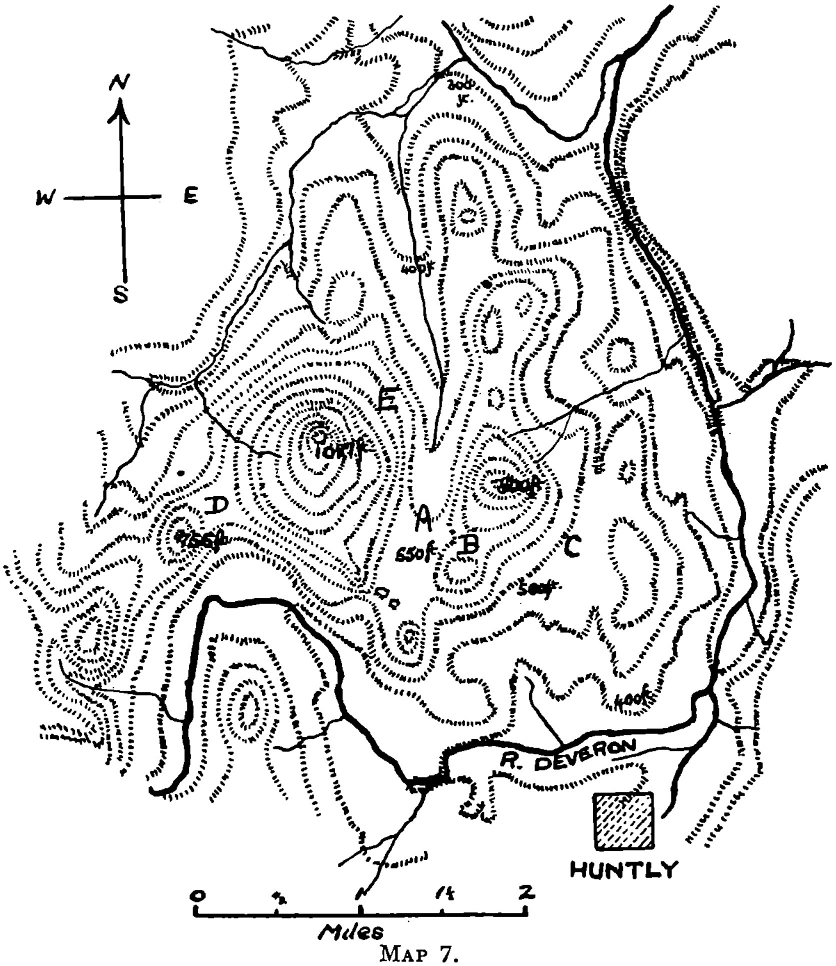
Hummocky, irregular Areas.—Fleet Forest on the Solway Firth and Fearnoch Forest on Loch Etive provide examples of areas which have a hummocky, irregular topography, full of little hills and hollows. On such areas each hollow is a potential frost pocket and often is also badly drained. In spite of their proximity to the sea both forests suffered considerable damage from the frosts of May 1935.

The narrow lowland Valley.—This heading is intended to include the type of narrow valley common in the Chiltern and Cotswold Hills. Such valleys are also common in other parts of the country. The distinguishing feature is that they are cut through a plateau which does not rise to any very great height above the valley bottom. There is, of course, a gradation between this type of valley and the narrow mountain valley so common in the highlands of Scotland, but the distinction consists chiefly in the height on the slopes.

Two such deeply cut steep-sided valleys in the Chiltern Hills are shown in Map 4 (page 117). The more southerly valley is Turville valley and the village of Fingest is situated at the junction. The shaded areas on the map are beech woods. Air at a damaging temperature collected at the head of Turville valley (Point A) approximately up to the 500 ft. contour line, judging by the injury to the beech. Lower down the valley, at Point B, it rose just above the 350 ft. contour. The woods in the bottom of the valley, Point C, had the whole of the leaves injured on the outside of their crowns, and the freezing air must thus have had a depth of at least seventy to eighty feet in these places. The section below the map shows that the valley slopes steeply at the head, but afterwards very gently.

Valleys of the same type are shown on Map 5 (page 118) in the Forest of Dean, where the freezing air banks up during a radiation frost in exactly the same way as in Turville valley. Indeed the oaks in the valley bottoms and on the lower slopes are frequently defoliated by spring frosts. The narrowness of these valleys in proportion to the area of the slopes which drain into them provides the chief explanation as to why the cold air banks up in them to so great a depth. There are, however, subsidiary but important factors which influence this. Turville valley, for example, debouches into another narrow valley and does this moreover at a point at which several valleys meet. The valley receiving them does not run straight on but turns at right angles, so that the katabatic winds which arise in each valley on clear, still nights do not have a clear run through, but meet with competing air currents where one narrow valley empties into another. The presence of woodlands in and across the valley, *e.g.* just above Point C, makes the run-off of the cold air still more difficult.

The difficulty in afforesting the bottoms of these narrow valleys is that there is no way of escaping the cold air. Shelter may give protection from loss of heat by radiation, but as has already been seen, unless it is very dense it is unable to keep out the freezing air which drains down from the higher ground. There is no way of preventing this and the result is that in really bad frost valleys it is difficult to raise satisfactorily some of the more tender of the commonly grown trees.



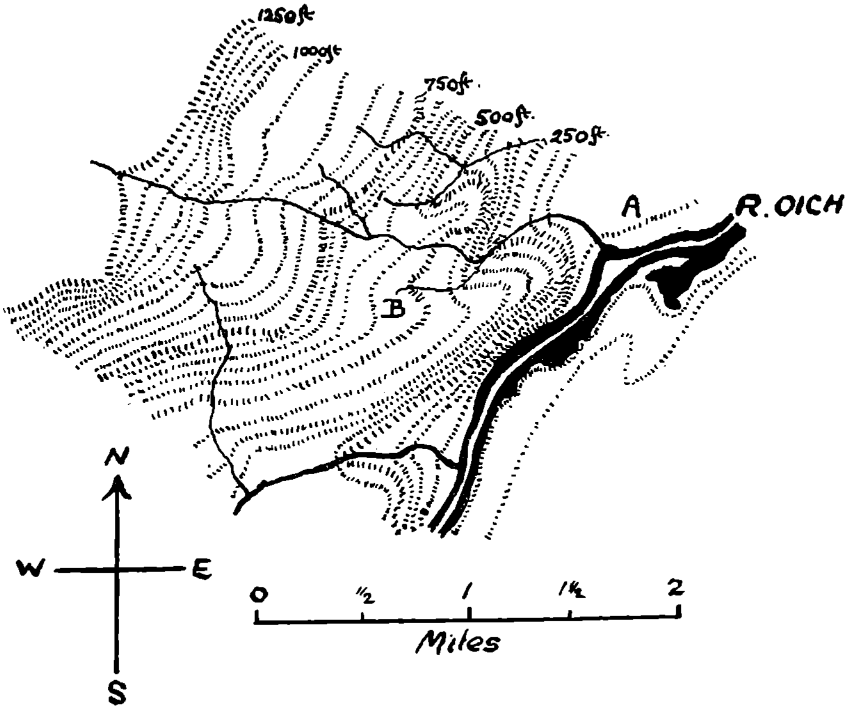
MAP 7.
Sketch map of the Bin Forest, Aberdeenshire.

The isolated Hill.—The Bin Forest in Aberdeenshire may be taken as an example. Actually the Bin covers two hills one of which is somewhat higher than the other, but together they form a compact group surrounded by appreciably lower land (Map 7). The River Deveron runs on the south and east, the Burn of Carnie on the north-west, leaving on the west a comparatively high col over which runs the road to Keith and Elgin. In between the two main hills lies Bin Moss (Point A), which, together with the surrounding low-land constitutes a frost hollow of the worst type (Plate IX, fig. 1). At Point B, on the lower hill, Ordiquhil, is a low col which is also a frost area. During the May frosts, 1935, spruce shoots were killed up to a height of fourteen feet at this point. The lower slopes of Ordiquhil at C also are subject to severe spring frostings. Records dating back to 1920 show that plantations of Norway spruce at this point were considered to be worthless owing to frost injury and, in places, many of the spruce have still failed to come through. Elsewhere on the hills the air drainage is good and the danger from frost slight as compared with Points A, B and C. Nevertheless during the May frosts, 1935, there was a certain amount of frost injury on the open slopes. Thus an appreciable amount of damage to new shoots occurred to the small trees at Point E and to rather larger Japanese larch and spruce situated on the western slope of the Bin above Point D.

The Mountain Side and Valley.—Many of the important forest areas of the future are to be found in the mountainous westerly and northerly parts of Britain. The salient features of such country are the greater length and steepness of the hill-sides when compared with lowland districts. The land at the higher elevations is often unsuited to tree growth. Thus there is commonly an upper planting limit between which, and the deep valley bottoms, there are often considerable differences in climate.

The Slopes of the higher Mountains.—A typical example is shown in Map 8. This shows part of Inchnacardoch Forest on the northern side of the Great Glen near Fort Augustus. The River Oich with the ship canal beside it runs at the foot of the slope. During the May frosts, 1935, severe damage to spruce occurred on the flat moors by the river side at Point A. On the slopes, however, the incidence of frost was very variable. The land was open deer forest until enclosed for afforestation. The steeper slopes were covered, more or less, with scrub woodland consisting of oak, birch and rowan. The conditions for growth where such woodland existed are comparatively good and the plantations are well established. In May 1935 frost damage here was slight, partly because the trees are now of some size (often ten or more feet high) and thus mainly out of colder air. Where, however, the slope is slight, or the ground flat or even hollow, as at Point B on the map, conditions for growth tend to become difficult. The difficulty lies largely in the condition of the soil, which may be shallow and often consists of a bad type of peat which is also badly drained. These hill-side flats are places particularly subject to frost injury; this is because the freezing air collects on them. When, as is the case at Point B, the configuration of the ground is slightly hollow very severe damage may occur. Plate IX, fig. 2 shows a small flat somewhat to the east of Point B on which the soil conditions are comparatively good but on which the frost damage was rather severe.

On account of the size of the trees but little idea could be obtained here as to the danger from frost to the steeper slopes; moreover there is much larch and Douglas fir on them, and these suffered less during the May frosts, 1935, than spruce. In Glenshiel and Ratagan Forests the planting consists mainly of spruce, even on the lower slopes. The forests are situated almost entirely on steeply sloping ground and there are no appreciable flat shelves such as are a marked feature of Inchnacardoch Forest. The part of Glenshiel Forest here referred to is situated on the lower slopes of Sgùrr a'Bhealaich Dheirg and opposite Sgùrr an Lochain. Both are mountains over 3,000 feet high. The glen is narrow; there is no appreciable width of flat land at the bottom and the mountains rise up steeply on either side. The forest has a south-westerly aspect. Its lower edge reaches to the road in the glen bottom, at an elevation of about 600 feet, while its upper edge rises to about 1,300 to 1,500 feet above sea-level. The Great Glen may be likened to a rather broad U with not very high sides, but Glenshiel is V-shaped with towering sides. It runs for about eight miles through two mountain walls which frequently rise to over 3,000 feet above sea-level, and the lower cols of which are over 2,000 feet high. The floor of the glen falls in height from about 890 feet to a few feet above sea-level. The distance across the valley from peak to peak is sometimes less than two miles as the crow flies, a very short distance considering the elevation of the mountains.

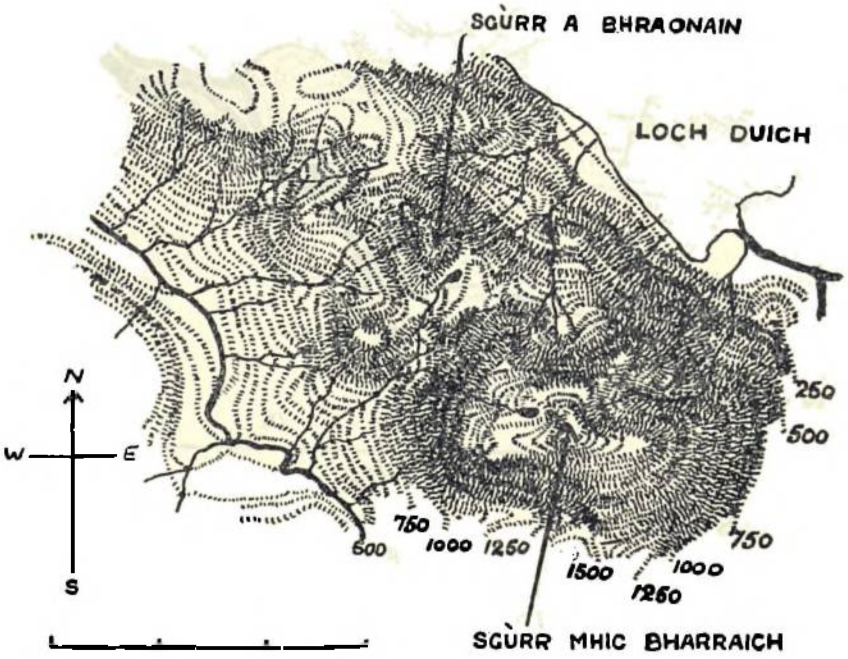


MAP 8.

Sketch map of part of Inchnacardoch Forest, Fort Augustus. The hills to the north rise to a height of 1,600–1,900 ft.

The main crop in Glenshiel Forest is Sitka spruce, the new shoots of which were frosted from the lower to the topmost limits of the forest. At the bottom the best trees were about eight feet in height, but most of them were smaller. The worst damage occurred at the lower edge of the forest, but even here it amounted in most cases only to the killing of the new shoots, comparatively few trees having any old wood killed. It is interesting to speculate as to the conditions under which this frost damage took place. It may be taken as practically certain that a radiation frost occurred. Either the glen filled with freezing air to the upper edge of the forest, or while only the lower part was so affected the upper was immersed in a current of cold descending air.

Ratagan Forest is situated at the mouth of Glen Shiel and on the sea at the inland end of Loch Duich (Map 9). It is of special interest because it has two marked aspects. On the loch side it faces north-east and on the opposite side south-west. The forest practically covers the hill Sgùrr a' Bhraonain which is just over 1,700 feet high. Part of the forest, however, is on the lower slopes of Sgùrr Mhic Bharraich, a mountain 2,558 feet in height. The planting is carried up to about 1,500 feet, descending to within 100 feet of sea-level on the loch side, and the greater part of the way down into Glenmore on the other. The situation is entirely different from that of Glenshiel Forest. Whereas that forest is on the lower slope of the sunny side of a deep and narrow valley, Ratagan Forest occupies the greater part of both the slopes running down from a ridge of variable height connecting two higher mountains. Comparatively, there is but little higher ground above it from which cold air can drain down, though Sgùrr Mhic Bharraich stands above it to the south. The situation is also different as regards the pooling of cold air. The upper slopes are of necessity free from this owing to their steepness, and on the lower slopes it is probably of much less importance. Thus the forest does not descend into the bottom of Glenmore on the south-west, while on the northerly side the sea loch is over a mile wide and provides much more room for cold heavy air to spread out.



MAP 9.

Sketch map of Ratagan Forest, Inverness-shire.

On the southerly aspect there was serious frost damage in May 1935, while the northerly aspect escaped almost entirely. The northerly aspect is the colder of the two owing to its comparative lack of sunshine in winter and spring. Because of this, the trees come into growth later than those on the southerly one. This was easily observed in the case of Sitka spruce. On the southerly aspect practically all the spruce had developed new shoots by the middle of May and all such shoots were killed. On the northerly aspect, however, even within a stone's throw of the sea most of the trees had only just begun to burst their buds. This was shown by a limited number of trees bearing a few short, dead shoots obviously killed as the trees were beginning to flush.

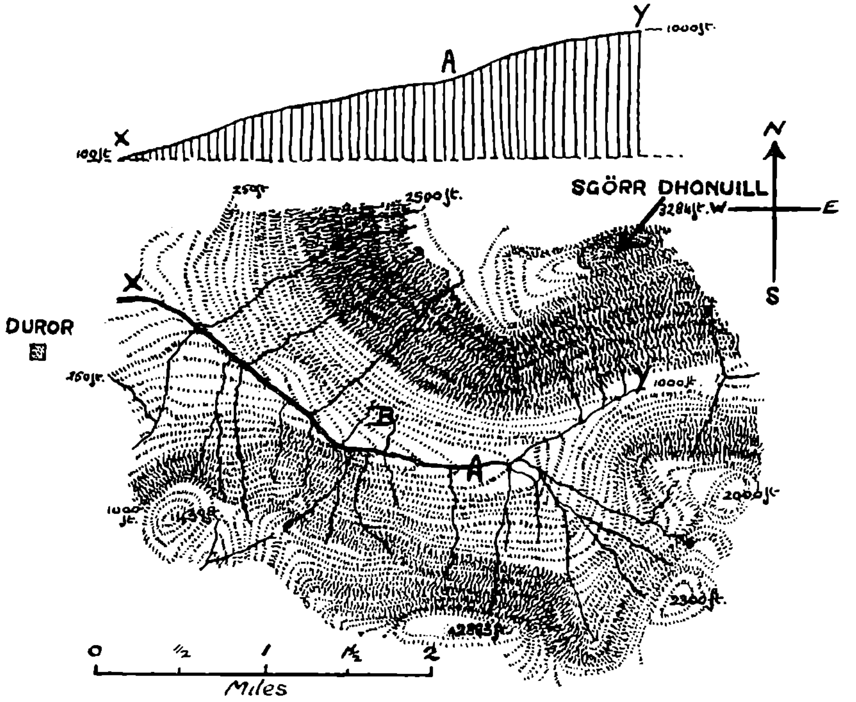
A further point to be noticed is that on the southerly aspect the damage was worst on the lower slopes. These were planted up before the higher ones but on the latter there are many trees quite well established. It was very marked that the length of dead new shoot on the frosted trees increased towards the foot of the slopes. There is a difference of more than a thousand feet between the upper and lower edges of the forest and this is enough to make an appreciable difference to the climate in which the trees grow. It would seem that the descending cold air on the slopes must in some cases have been at least six or eight feet deep, trees of this height being frosted to the top. It is possible that the trees themselves help to prevent the draining away of the cold air which surrounds them. This seems to be a factor which is probably of importance even on a steep slope.

The Valley in the higher Mountains.—The general conclusion to be drawn from the previous section is that, on the sides of the higher mountains in this country, a position on a steep open slope above a valley bottom does not of necessity ensure that a small tree shall be out of the freezing air when there is a severe ground frost on clear, still nights. In such a position there are always higher slopes from which cold air may drain down. There is, however, a great lack of data regarding the descending currents of air and the height to which cold air collects in the valley below. Some further evidence with regard to this will be brought forward in connection with three highland valleys, namely Glenduror and Glen Righ in Scotland, and the valley of the Afon Trystion, which opens out into the valley of the River Dee at Cynwyd, near Corwen, N. Wales. In all these the forest descends right to the bottom, and in two cases clothes both the sides of the valley.

(i) *The short steep open Valley.*—Glen Duror runs from east to west and the forest is situated mainly on the northern side at the foot of Beinn a' Bheithir. This mountain rises to a height of over 3,200 feet and to some 2,500 feet above the lower edge of the forest at the head of the glen. The westerly half of the forest has a south-westerly aspect while the easterly half mainly faces south. The slope is steep, on the whole, and there are no important flat ledges as at Inchnacardoch. At the exposed westerly end the planting goes up to 1,000 feet and at the more sheltered easterly end to 1,500 feet. Map 10 gives some idea of the general situation. Loch Linnhe, a sea loch about four miles wide here, is within a mile and a half of the mouth of the glen. Glenduror is a short valley with a wide mouth, but a rather narrower and more enclosed upper end which is surrounded by mountains on three sides. The gradient is comparatively steep (*see* section X–Y on Map) being least at the Point A. There is no flat land except at the upper end and the valley sides are steep, and precipitous on the upper slopes. The forest escaped very lightly from the May frosts, 1935, except in the flatter part at Point A. This piece of the forest is shown on Plate X, fig. 1, taken just beyond the ruined house of James Stewart (Point B) who will be remembered by readers of R. L. Stevenson's book "Kidnapped". A shoulder projects on the north side at this point so that there is an obstruction to the air flow down the bottom of the valley.

The point to be brought out here is that, in spite of the long steep slopes which line the glen, frost damage was only severe where the free downward flow of air was obstructed. The short, open-mouthed glen evidently permits the descending air currents to flow out and disperse over the sea. It would seem that the depth of these currents on a slope depends not a little on the depth of the cold air in the valley. Where free outflow is available, as in the lower half of this glen, there can be little pooling up of cold air in the valley bottom and so any severe damage which may occur is usually confined to local hollows on the slopes or where there is any form of obstruction to the downward flow of cold air.

(ii) *The narrow flat winding Valley.*—Glen Righ is situated in the foothills of Mamore Forest, the highest point of which is Ben Nevis, and opens out on to Loch Linnhe just below the Corran Narrows. This glen is drained by a small stream, the Amhainn Righ, which follows a slow and in places very winding course down the flat and often marshy glen bottom (Plate X, fig. 2). The

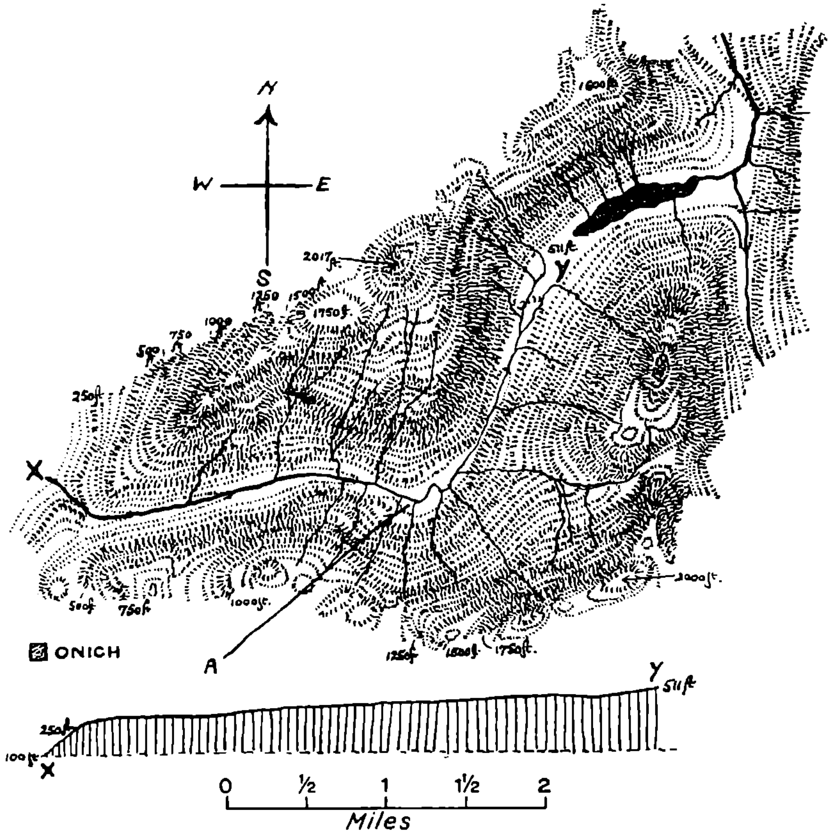


MAP 10.

Sketch map of Glen Duror, Argyllshire. A straightened section is given along the bottom of the valley from X to Y.

glen is narrow, has several sharp turns and is rather steep sided (Map 11), with the hills on either side rising up to about 2,000 feet above sea-level. The forest area of interest here is situated at the top of the glen, which at this point runs from N.N.E. to S.S.W. The aspects of the two sides are therefore E.S.E. and W.N.W. The planting has been carried up to about 1,100 feet above sea-level on either side. The eastern aspect is the warmer, better drained, and provides the better conditions for growth. The frosted shoots suggested that flushing was further advanced on this slope than on the colder and less well-drained westerly slope. New shoots of Sitka spruce were killed by the May frosts, 1935, from the upper limit of planting down to the valley bottom. The trees in the valley bottom had longer shoots, and obviously had been further advanced in growth at the time of the frosts; it was here that damage occurred sufficiently severe to cause the death of shoots more than one year old.

It seems certain that extensive pooling of cold air took place in this glen but it was difficult to estimate how far up the slope the cold air actually reached. On the upper four-fifths of the slopes the damage affected the new shoots only and appeared to be equally severe everywhere. Only further observation can show whether on clear, still nights, cold air is capable of banking up to above the limit of planting, some 600 feet above the bottom of the glen, or whether it was the downward flow of cold air which caused the damage in the 1935 frost.

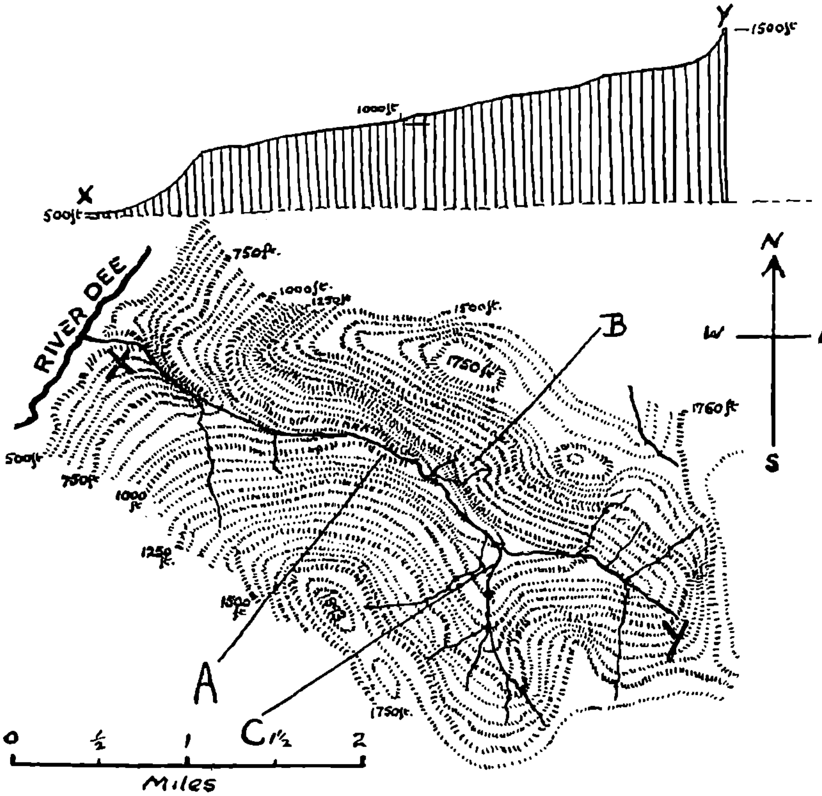


MAP 11.

Sketch map of Glen Righ, Inverness-shire. A straightened section is given along the bottom of the valley from X to Y.

(iii) *The Valley with moderately sloping Sides.*—The valley in which Cynwyd Forest is situated is much less steeply sided than either Glenduror or Glen Righ but during the lower two-thirds of its course the Afon Trystion runs through a small ravine (Map 12 and Plate XI, fig. 1). This forest was not visited in 1935, but a visit had been made in the previous year to study frost damage. The valley bottom is a frost hollow. The valley has a comparatively wide drainage basin at its upper end on the slopes of the Berwyn Mountains which here rise to a height of over 2,000 feet. The valley narrows until the Point A is reached when it widens out considerably. The general course of the valley is from east to west, giving northerly and southerly aspects to its slopes.

Where the valley bottom narrows to a ravine, the southerly slope is semi-precipitous, but on the northern side there is an appreciable flat area which rises towards the steep ravine side in a series of flat steps. On these steps and in the flat bottom the damage was very severe. The crop at Point A on the map was European larch, and was badly frosted. On both the steep sides the amount of injury was much less severe, and may be described as only slight on the upper half of the slopes. Some further investigation of frost damage was made at Point B (Plate XI, fig. 1) where the steep rise of the ravine gives way to a gentle slope. Some of the Sitka spruce growing here had been cut back severely by frost, while the frost rings in the externally uninjured trees showed that the whole plantation had very narrowly escaped severe damage. The injury to the trees showed that at this point air cold enough to cause very marked frost-ring development



Map 12.

Sketch map of Cynwyd valley, North Wales. A straightened section is given along the bottom of the valley from X to Y.

and some severe injury lay to a depth of at least seven feet. Nevertheless some Norway spruce on the steep upper slopes of the ravine, just below, had apparently escaped without appreciable damage. There appeared to be a definite correlation at this place between steepness of slope and amount of frost injury, and this is true of other recently afforested areas near Corwen. Where the slope is steep the frost damage is usually slight, whereas if it is gentle severe injury is liable to arise, even though there may be steep slopes above and below. Another example of the blockage of air drainage, which occurs when a valley narrows, is shown in Plate XI, fig. 2. This shows the lower part of a gently sloping valley head in the Sluggan Valley, Glenmore Forest, which is subject to severe frost owing to the manner in which the valley narrows.

It is concluded that in valleys where the mountain side rises high up above the forest liability to severe frost damage depends largely on steepness, width and length of the valley, the gradient of the valley bottom and the space available for the cold air to disperse as it flows out of the valley. The short, wide, steeply graded valley, which debouches on to a wide open space, such as the sea, is most likely to escape damage from radiation frosts. In the narrow, steeply sided valley even a situation hundreds of feet above the valley bottom is not necessarily immune from severe spring frosts.

The Slope and Valley in the lower Mountains.—Newcastleton Forest, on the Border, provides an example of this topographical type. The forest covers smooth, rounded hills which are about 1,200 feet in height and are afforested to the top with Sitka spruce. The data given in the table below apply to a north-facing slope above Tweedenhope Burn and show that the amount of damage caused by the 1935 frosts was largely affected by the elevation.

Elevation in Feet.	Percentage and Height of Trees in Damage Classes.											
	Little or no Damage.		Only side Shoots damaged.		Leaders dam-aged.		Some older Wood dam-aged.		Cut to the Base.		Dead.	
	%	Ht. (feet)	%	Ht. (feet)	%	Ht. (ft.)	%	Ht. (ft.)	%	Ht. (ft.)	%	Ht. (ft.)
650	9	5½	8	6	23	6¼	53	5¾	5	4½	2	2
750	36	5¼	10	5¼	38	5	10	4	—	—	6	2
800	40	5½	20	5¾	28	5¼	10	3¼	2	2	—	—
900	58	7	22	5¼	12	5¼	6	2½	—	—	2	2
1,000	76	7	20	6¼	4	5½	—	—	—	—	—	—

The trees at 650 feet elevation were in a frost hollow and near the burn. It appears that the more severely damaging temperatures were limited to a comparatively shallow and narrow belt in the valley bottom.

There was evidence also at Newcastleton to show that where the slopes flatten out, frost pockets occur irrespective of elevation or relative situation. On the top of the ridge on this area there is one of these rather flat and frosty places. An example of such a frosty flat in country of this type is shown in Plate XI, fig. 3 which illustrates part of Durris Forest in the Dee Valley near Aberdeen.

Conclusion.

Sufficient examples have probably been given to convince the reader that the relationship between topography, frost intensity, and damage to young trees is by no means simple. It has been shown that topography, by checking or promoting the flow of cold air, plays an important part in regard to frost intensity. The degree of damage, however, often depends more upon the stage of development of the buds at the time of the frost than upon the local air currents. The bud stage, in its turn, may be affected by aspect and degree of slope, thus bringing the argument back once more to topography. Other factors such as (i) the relationship of slope to soil conditions which in turn may affect the rate at which a young tree grows out of the frost zone; (ii) exposure to the morning sun, and (iii) shelter from wind, must also be borne in mind. It is from the interaction of some or all of the above factors that the cause of any given case of frost damage must be sought.

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FIG. 1.

Severely frosted Sitka spruce at West Tofts, Thetford, Norfolk. All the young shoots were killed by the May frosts. The rod is four feet high.

Photo : M. Njmmo, May 1935.

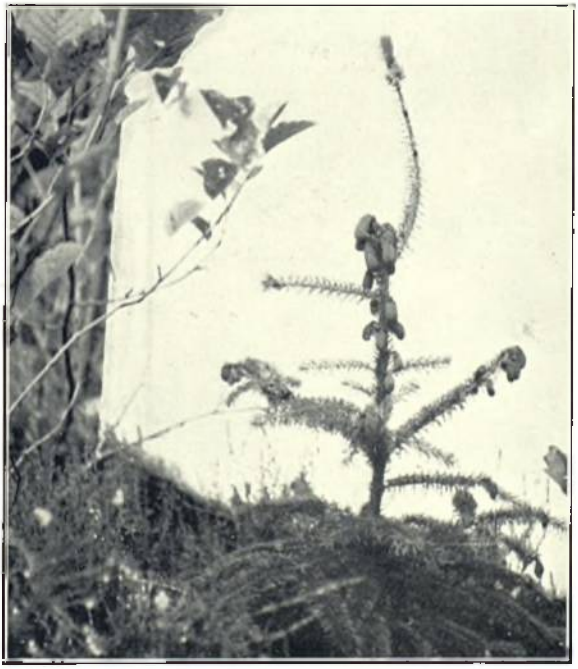

FIG. 2.

Sitka spruce in Portclair Forest, Inverness-shire, showing the emergence of a new leading shoot after the original leader and most of the other new shoots had been killed by the May frosts. This tree was sheltered both at the sides and above by common alder.

Photo : J. Fraser, summer 1935.

PLATE II.

FIG. 1.
Douglas fir and Scots pine at Swaffham, Norfolk. An early flushing Douglas fir on the right has been severely damaged. A late flushing Douglas fir on the left and a Scots pine in the centre have suffered no apparent damage.

Photo : M. Nimmo, 21st May, 1935.

FIG. 2.
Beech, 23 inches high, from Thetford, Norfolk. The lower part was badly frosted on 26th May, 1934, but the top which was above the layer of coldest air was undamaged.

Photo : M. Nimmo, June 1934.

PLATE III.

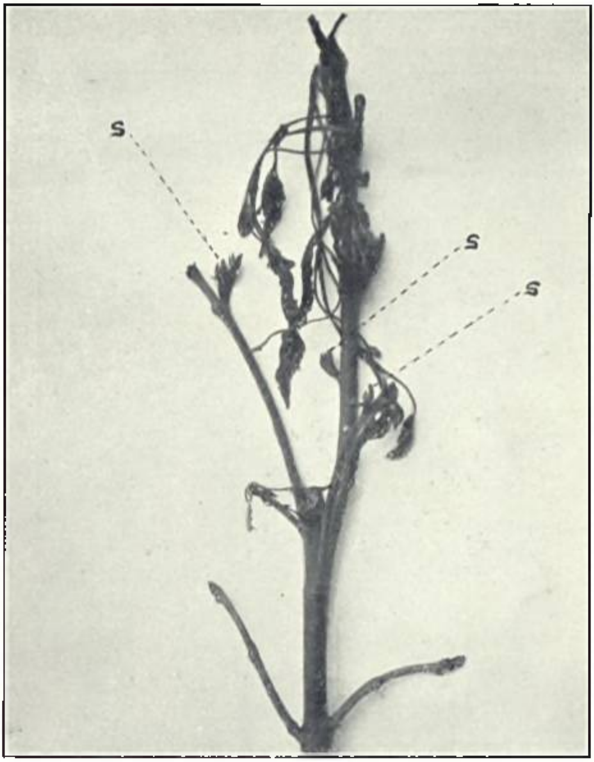

Fig. 1.
Twig of ash taken soon after the frost showing shrivelled leaves and the appearance of new shoots (S).

Photo : M. Nimmo, May 1935.

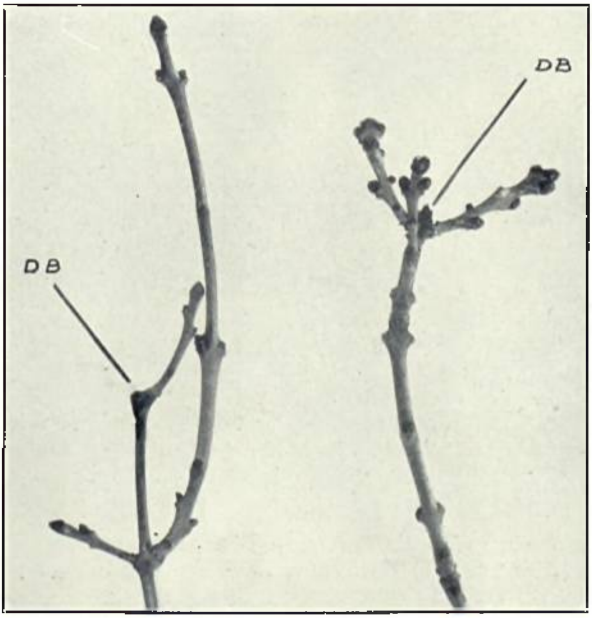

Fig. 2.
Twigs of ash known to have been considerably frosted in May 1935. DB indicates dead bud.

Photo : L. A. Clinkard, January 1936.

FIG. 1.

Sitka spruce in Glen Righ, Inverness-shire, with two years' wood killed by the May frosts. The total height of the tree was 3½ feet.

Photo : J. Fraser, summer 1935.

(*a*) (*b*)

FIG. 2.

Oak and two elms (in background) near Basingstoke. Photographed (*a*) 19th June, 1935, and (*b*) 19th June, 1936, showing the complete recovery of the oak and the lack of damage to the elms.

Photos : H. Henshaw.

Fig. 1.
Sitka spruce dwarfed by repeated frosts at Delamere, Cheshire. This tree was planted in 1922.

July 1934.

Fig. 2.
European larch severely damaged by frost in Cynwyd valley.

July 1934.

FIG. 1.

Position of Point A in Tables XL and XLI. Point C is in the birch belt in the background, near Olley's Farm, Thetford.

FIG. 2.

Position of Point B in Table XL, near Olley's Farm, Thetford.

Photos : M. Nimmo, February 1936.

FIG. 1.
Scattered trees left to provide overhead cover to ash, sycamore and spruce at West Grimstead, Wiltshire. The shelter was ineffective against the frosts of May 1935.

September 1935.

(*a*) (*b*)

FIG. 2.
Canopy above Point A in Tables XL and XLI photographed (*a*) in February and (*b*) in June 1936.

Photos : M. Nimmo.

PLATE VIII.

FIG. 1.
Ash coppice at Buriton, which effectively protected young beech in the frosts of May 1935.

September 1935.

FIG. 2.
Girdled oak and birch scrub in Mortimer Forest. This gave protection to larch growing in a good situation.

September 1935.

PLATE IX.

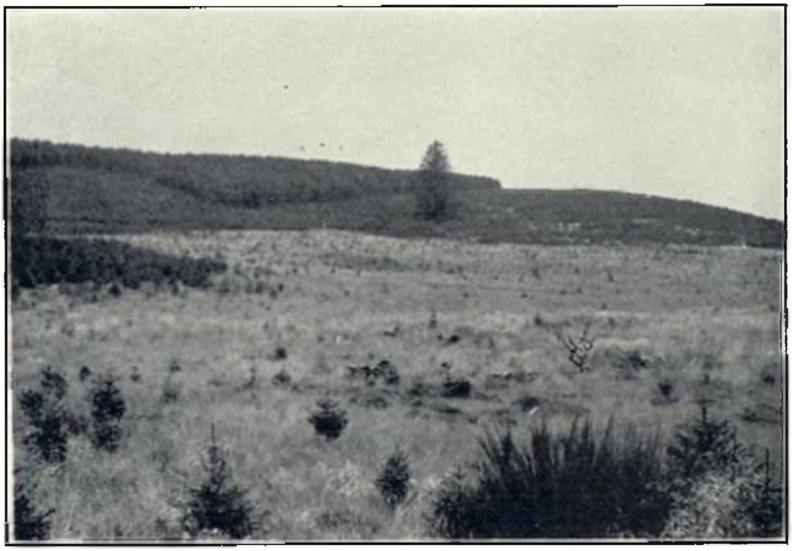

FIG. 1.

The edge of Bin Moss, Aberdeenshire, Point A on Map 7.

October 1935.

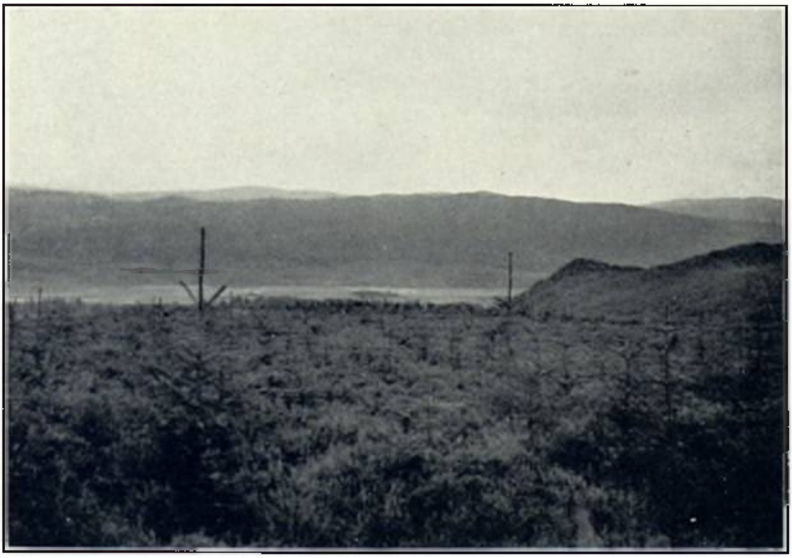

FIG. 2.

Norway spruce on a frosty flat at Inchnacardoch, Fort Augustus. The Great Glen can be seen in the background.

October 1935.

Fig. 1.
Frosty flat in Glen Duror, Argyllshire, Point A on Map 10.
October 1935.

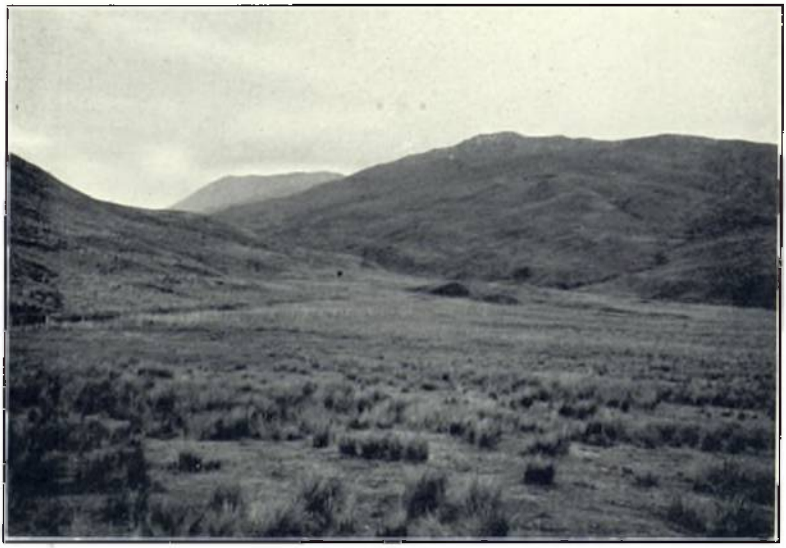

Fig. 2.
Glen Righ, Inverness-shire, taken from Point A on Map 11 looking North-east.
October 1935.

PLATE XI

FIG. 1.
Cynwyd valley in North Wales, looking south from near Point B on Map 12.
July 1934.

FIG. 2.
Frosty flat at the head of Slugan valley, Glenmore. The foreground slopes towards the steep-sided valley in the background. The narrowness of this valley restricts the drainage of cold air which tends to collect on the area shown in the foreground.
August 1936.

FIG. 3.
Frosty flat, Durris Forest, Aberdeenshire; the ground slopes very slightly towards the right background.
July 1936.

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4. The Black Pine Beetle (*Hylastes ater*).
5. Conifer Heart Rot (*Fomes annosus*).
6. Honey Fungus (*Armillaria mellea*).
7. Chermes attacking Spruce and other Conifers.
8. Douglas Fir Seed Fly (*Megastigmus spermotrophus*).
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13. The Larch Longicorn Beetle (*Tetropium gabrieli*).
14. The Phomopsis Disease of Conifers (*Phomopsis pseudotsugae*).
15. The Felted Beech Coccus (*Cryptococcus fagi*).
16. Larch Canker (*Dasyscypha calycina*).
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