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SHELTERBELTS AND MICROCLIMATE

By

J. M. CABORN, B.Sc., Ph.D.

DEPARTMENT OF FORESTRY
EDINBURGH UNIVERSITY

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EDINBURGH: HER MAJESTY'S STATIONERY OFFICE
1957

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FOREWORD

The influence of the wind on forests and agricultural crops has for long occupied the attention of husbandmen. Many shelterbelts have been established in various parts of the country, and there is general agreement that, when these are properly sited, benefits accrue to the farmlands in their vicinity. But hitherto there has been little research into the reasons for this, and few attempts have been made to measure the effect of the belts upon the winds that they deflect, or upon other factors of the microclimate.

From 1953 to 1955, Dr. J. M. Caborn carried out a series of original investigations at the Edinburgh University Forestry Department, with the aid of a grant from the Forestry Commission, into this important subject. This Bulletin presents the results of his researches, which were conducted partly in the laboratory and partly among actual shelterbelts in the Edinburgh district. It is believed that his conclusions will be of value to agriculturists as well as to foresters.

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CONTENTS

AUTHOR'S PREFACE

This bulletin is the outcome of research undertaken within the Department of Forestry of the University of Edinburgh between 1953 and 1955 into the effects which belts of trees exert on the microclimates of their adjacent regions.

Part One consists of a review of available scientific evidence concerning such effects and their influence on agricultural yields and forestry practice. Part Two deals with a critical survey of research procedure in connexion with microclimatological investigations of shelterbelt effects. Experimental work undertaken is described in Part Three and discussed in relation to its practical application to shelterbelt requirements in Great Britain.

In presenting this work, acknowledgment is due to all those who have contributed towards its completion: the Forestry Commission and Edinburgh University for bearing the expenses of this research project; Professor P. A. Sheppard, B.Sc., F. Inst.P., of the Department of Meteorology, Imperial College of Science and Technology, London, for wind-tunnel facilities provided and for advice and encouragement; the Danish Heath Society for facilities to study shelterbelt technique in Denmark; Dr. Werner Nägeli of the Swiss Forest Research Institute, Zürich, for similar facilities in Switzerland and for advice and demonstration of experimental methods used in microclimatic study; the Meteorological Office for preliminary advice and for the loan of instruments; Dr. Martin Jensen of the Royal Technical College, Copenhagen, for initial guidance regarding wind-tunnel research and for the gift of swinging-plate anemometers; the many proprietors and occupiers of land who have readily allowed access to their properties for the collection of field research data; Mr. J. L. Harrison for photographs reproduced in Plates 9, 10, 14, 16, 17, 19, 20, 21, 22, 23, 25, 26 and 27; authors as indicated for reproductions of diagrams in Part One; the Department of Forestry, Edinburgh University, for all remaining photographs; the Director General, Ordnance Survey, for permission to reproduce maps; Professor M. L. Anderson, M.C., M.A., D.Sc., Professor of Forestry in the University of Edinburgh, for advice, encouragement and practical assistance throughout and, finally, the members of the teaching staff of the Department of Forestry, Edinburgh University particularly Dr. W. E. S. Mutch and Dr. W. A. Fairbairn and Mr. J. L. Harrison, for their considerable help with the investigations.

Edinburgh,
21st March, 1956. J. M. CABORN

ABSTRACT

The available evidence of microclimatic and associated biological influences of shelterbelts and their economic significance with regard to agricultural productivity and forestry practice is reviewed. The applicability of previous research to shelter requirements in Great Britain is considered and certain general conclusions regarding belt types, layout and structure derived. Possible extension of investigational work from a forestry aspect is outlined. Experimental technique and instrumentation for the study of shelterbelt effects on microclimatic factors, particularly wind, are examined in some detail.

Fundamental research on two features of shelterbelt design, the effects of windbreak width and cross-sectional profile on the pattern of the leeward sheltered area, involved wind-tunnel studies. Field investigations of microclimate in the vicinity of tree belts concentrated on the assessment of their efficiency on the basis of their effect on wind abatement and their general structural and silvicultural condition, and were exploratory studies directed towards ultimate selection of ideal shelterbelt structures.

The width/height ratio in windbreaks has a significant effect in determining the extent and nature of the leeward sheltered zone; this may be apparent only when the degree of penetrability to the wind falls below a critical value, estimated to be 20 per cent. Wide belts appear to lead the wind parallel to their upper surfaces with consequent, rapid, downward transfer of energy after leaving the leeward edges and restriction of the leeward eddy zone, giving rise to early resumption of the unobstructed wind velocity and a reduction of the distance protection afforded. Optimum belt widths will vary according to species and planting density; wide belts will exhibit a low efficiency index during their early years.

The fundamental effect of a slope on the windward margin of a windbreak is to minimise resistance to the normal flow pattern of the wind; this is of importance in connexion with marginal protection of forests, but disadvantageous with regard to shelter near the ground. An inclined windward edge causes deflection of the major part of the air stream over the windbreak, thus reducing the effective degree of penetrability, similar to an increase in width. The sheltered zone is restricted to a degree dependent upon the acuteness of the angle of this gradient.

The sheltering efficiency of a belt may be determined by measurement of wind relationships within its range and subsequent comparison with corresponding values for a standard, moderately penetrable shelterbelt. This procedure offers a simple "rule-of-thumb" method for assessing treatment necessary to preserve or promote efficiency and ensure continuity of the stand. The shelterbelts studied are examined in the light of their present and potential efficiency.

The practical application of these results to the design and maintenance of shelterbelts and their contribution to eventual determination of the ideal shelterbelt are discussed, together with shelterbelt technique in forestry practice, modification of wind conditions in relation to the siting of shelterbelts on upland areas and possible aspects for future research.

PART ONE

REVIEW OF PREVIOUS LITERATURE

Chapter 1

HISTORICAL

IN THE DEVELOPMENT of a scientific approach to the technique of planting forest belts and narrow strips of trees for shelter against wind and storm, America, Denmark and Russia have been most prominent. During the last century or so these countries have been faced with the problem of settlement or re-settlement of peoples on former prairie, heathland or steppe, regions where the provision of shelter was of primary importance. Their problems were comparable in that all were concerned with the reclamation, mainly for arable farming, of vast areas where the chief limiting factor to plant growth was moisture. Shelterbelts were established in these regions with the object of conserving soil moisture by reducing evaporation from, and wind erosion of, the light, friable soils and by controlling the distribution and later melting of snow in steppe and prairie. As these large-scale projects developed successfully, scientific investigation of the influence of shelterbelts on the physical factors of the microclimates of protected areas, as well as detailed research into the effects on the yields of arable crops, gradually followed. By means of practical experience and continuous study, a wide knowledge of the cultural problems relating to shelterbelt technique, the design and construction of suitable belt types, has accumulated in these countries.

It is apparent that many other countries, including Great Britain, had for a long time accepted the scattered woodlands, shelterbelts and hedgerows as a necessary feature of an agricultural countryside, although they may not have fully appreciated their shelter value. However, there is evidence that the value of shelterbelts was realised in the rehabilitation of the East Anglian Breckland soils in the 19th century and also by the Scottish agricultural improvers of the 18th and 19th centuries, when shelterbelts and plantations were employed as one of the foundations of development of exposed and marginal land. These developments were lost sight of in the industrial age which followed.

Similarly, in Germany, Hungary and Switzerland, the advantages of shelterbelts were being publicised during the early 19th century and the observations of many early writers in this connexion have since been confirmed by scientific research. One of the most interesting of such reports based on observation of shelterbelt influences is that of the German agricultural and forestry adviser, Albrecht, written in 1832 (Hilf 1951). Following bad harvests in the Westerwald in 1816 and 1829, and the adversity which they occasioned, the Nassau government called upon Albrecht to report on the affected areas. The forests of the Westerwald plateau had been almost completely devastated for charcoal production; a harsh, unfavourable climate resulted and the agricultural prosperity declined seriously. Albrecht's plan was not reforestation as such but the establishment of shelterbelts and plantations for the shelter of villages and fields against the wind. He claimed that, without such shelter, neither grass nor cattle could be produced from the land. Though not started until after 1840, towards 1850 the favourable effects of the shelterbelts planted were visible, as fully predicted by Albrecht, and his scheme found general recognition amongst the people. These successes were, however, local and were not of such national importance as the American, Danish and Russian projects, to which one must turn for early scientific evidence of the influences of shelterbelts.

Original Russian research on this subject may be said to date from the mid-19th century, when Graff organised the planting of the Veliko-Anadol forest in 1843-44 with the idea of combating drought and demonstrating the possibilities of afforestation in the extensive steppe regions of Russia and the Ukraine. Pioneer research workers gradually followed and one of the earliest published papers appears to be that of Shatilov (1893), based on five years of investigations. Several publications appeared subsequently but very full data on the effects of tree-belts on microclimate and crop yields were not obtained until after 1931, when the broad development of scientific research and field-scale operations in connexion with agricultural improvement by means of forestry was initiated. Since 1931, extensive investigations have been undertaken by the resultant organization (known as VNIALMI) into the various microclimatic factors, both individually and collectively, the latter chiefly in relation to agricultural productivity in the sheltered areas. Conclusions have been reached as to the best type of shelterbelt, in terms of width, density, structure and distance between the belts, for Russian steppe conditions with their expansive, flat areas subjected to an extreme Continental climate. Few of the Russian papers have concerned undulating country.

In America, great progress has been made during the present century, and especially since the severe drought of 1934, in shelterbelt planting for rehabilitation of prairie farmlands. Between 1934 and 1941 four million acres of farmland were protected in the Northern Great Plains. Since Bates' (1911) valuable paper on the influence and value of windbreaks, continued study has been made on their advantages and disadvantages, selection of species for, and composition of, the belts and their treatment. A considerable quantity of literature has been published on these various aspects but the contribution to microclimatic information has been limited.

As early as 1901, Canada began the free distribution of trees to farmers in the Prairie Provinces for shelter planting, which concentrated mainly on establishing windbreaks near the farmsteads for providing protection to people, livestock, gardens and buildings. Since 1930, more attention has been paid to the planting of field shelterbelts with the intention of improving conditions for growing crops. Under the Prairie Farm Rehabilitation Act, 1935, experimental stations have been established to investigate the particular problems of these regions. As in the United States of America, emphasis has been laid on the control of wind erosion.

In 1866, the engineer, Dalgas, founded the Danish Heath Society to develop the sandy, heathland areas which then covered a large part of Jutland. In 1910, the Society began a period of scientific, "agrometeorological" investigation into crop yields. Previously the amelioration of climatic conditions and the land, due to the provision of shelter, had been accepted as self-evident. Early research data, although confirming the results of Professor La Cour (1872), were too vague to be satisfactory and it was not until about 1936 that Flensborg, the Director of the Heath Society, formulated the idea of investigating shelter-effect initially from a pure, physical aspect, namely by using a wind-tunnel. Investigations made in the "wind laboratory" at the Royal Technical High School, Copenhagen, were afterwards translated to actual field conditions. In the meantime, the reclamation work of the Society progressed rapidly and large tracts of heathland are now covered with a systematic network of narrow shelterbelts and hedgerows and converted into productive farmland.

In Switzerland, with rich, alluvial plains bordered by mountain ranges which form "funnels" for the wind, shelterbelts were planted to some extent towards the end of the 19th century. Examples of such planting are the Rhine and Rhone valleys. But it was not until recent years, as a result of detailed study of wind conditions in the vicinity of existing shelterbelts and the intensification of agriculture in these plain areas, that the establishment of belts of approved types was initiated.

Comprehensive schemes of research into the beneficial effects of shelterbelts to agriculture have been resumed in Germany since the 1939-1945 War and valuable data are being added to the early work of Woelfle, summarised by Woelfle (1950) and Geiger (1950); this early research, much of it from a forest meteorological aspect, has formed the basis for many subsequent investigations.

Japan has contributed recently to scientific knowledge of the sheltering influences of particular shelterbelts and studies, following the Danish and Swiss patterns, have been made of microclimatic factors in Holland, Italy and Czechoslovakia.

Occasional research has been undertaken also by individual workers in several countries of the Commonwealth. Increased yields of agricultural and horticultural crops due to the shelter have been reported from Argentine, France, Hungary, Italy, Japan and Sardinia as well as from those countries where continuous research has been carried out.

A survey of the available literature reveals that the majority of countries where research on shelterbelts has been undertaken has been concerned with the reclamation or improvement of agricultural plain areas and not with upland regions.

Chapter 2

THE INFLUENCE OF SHELTERBELTS ON MICROCLIMATIC FACTORS

BELTS OF TREES which obstruct the flow of the wind reduce the velocity of the air currents in the lower layers of the atmosphere and produce a sheltered zone in the vicinity of the belts. A "local" or "micro-" climate obtains in this sheltered area, having characteristics different from those in unsheltered regions. Different structures of shelterbelts, in terms of width, height, composition by species and penetrability to the wind, have distinct effects on the character of the microclimate, which is frequently referred to as the "climate near the ground" and, for the purpose of this paper, is considered generally as the first two metres above ground level. The nature of the microclimate can be assessed by measurement of the physical factors which it comprises, i.e. wind velocity, air temperature and humidity, evaporation, transpiration, snow lodgement, soil moisture and temperature, and also by biological means such as measurement of the yields of agricultural and horticultural crops grown in the sheltered area.

A considerable amount of scientific evidence of the effects of shelterbelts on microclimate has been published during the present century but few papers have attempted a comprehensive summary of universal research in this field. Nägeli (1941) summarises shelterbelt influences in relation to practical protection of agricultural crops but he omits important Danish contributions (Nøkkentved 1938, 1940) and early circumstantial work in the United States of America (Bates 1911). An adaptation of this summary has been made in Dutch (Fransen 1942). A detailed survey of literature on each factor of the microclimate by van der Linde and Woudenberg (1951) does not include recent Russian research, which is critically presented, however, by Gorshenin (1941, 1946). German work has been reviewed by Kreutz (1952b) and Hennebo and Illner (1953).

Although not dealing specifically with the effects of shelterbelts, Geiger (1950) gives much useful information on the climatic elements of the lower air layers and general forest influences, the latter being dealt with also by Kittredge (1948) and Woelfle (1950).

In recent years scientific investigation of shelter effects has shown a tendency to greater consideration of aerodynamics and, on account of the many difficulties of field research, more studies have been undertaken in the laboratory by means of wind-tunnels. Several investigations have also employed model windbreaks in the field instead of natural tree belts. These studies have shown that reference to some of the standard texts on fluid dynamics is necessary for a closer appreciation of the action of shelterbelts. Allied research on the pattern of air flow has contributed much valuable information on this subject and has been included, where applicable, in the following review of literature, which treats each physical factor of the climate near the ground separately as far as this is possible.

Section 1. Wind

Pattern of Air Flow Near the Ground

Investigations in the fields of aerodynamics and meteorology have shown that atmospheric wind flows more or less parallel to the ground surface and increases in velocity with height above ground. As the air flows over a boundary surface, such as the ground, a frictional drag develops according to Prandtl's boundary layer theory (Goldstein 1938). Coupled with the laminar movement there is a vertical exchange of the energy of motion between the air

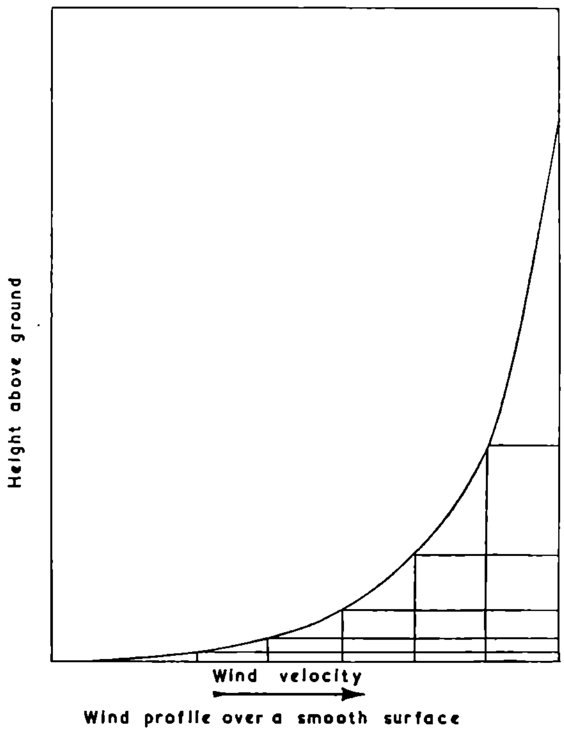


FIGURE 1. Wind profile over a smooth surface, illustrating the effect of frictional drag.

masses by means of eddy diffusion. In this way the braking effect of the boundary surface is transmitted upwards, for each parcel of air moving upward carries with it the lesser horizontal motion which it possesses and, coming in contact with faster-moving layers, exerts a braking action on them through its inertia. Directly at the surface there is a marked increase of velocity with height until the limit of the zone of frictional drag (see Fig. 1).

The wind profile near the ground depends upon the roughness of the surface, the influence of which extends upwards according to the surface dimensions. Hellmann (1915, Geiger 1950), in discussing wind research at Nauen, stated that an anemometer, placed at a height of 2 m lost velocity if the grass beneath it were full grown. The grass had the effect of bringing the ground closer to the anemometer. In its braking action on wind velocity the surface of the ground was no longer effective at height $z=0$ but at another hypothetical surface at height $z=z_0$. The value z_0 evidently depends on height and kind of plant cover; it is called the "roughness height", z_0.

In an experimental study of roughness, Paeschke (1937) obtained the following results, which are similar to those recorded by Nøkkentved (1940).

Kind of soil or plant cover	Roughness height, z_0 cm
Smooth surface of snow	3
Göttingen airport–short grass	10
Bracken	10
Low grassland	20
High grassland	30
Turnip field	45
Wheat field	130

In the forest the "roughness height" increases to quite different magnitude and the part below z_0 belongs to the calm trunk space (Geiger 1950).

Plant cover and, similarly, obstacles such as shelterbelts, placed in the path of the wind, create a new boundary surface of separation at an elevation approximately equal to the height of the obstacle. The drag on the original surface is lessened and the prevailing surface velocity lowered. Thus the direct force of the wind on the ground is decreased.

Effect of a Barrier and Shelterbelt on Air Flow

The approximate surface of separation to leeward of a cross-wind barrier is shown in Fig. 2, which also illustrates the formation of a zone of eddying flow behind the barrier. This zone gradually merges into the "wake" of the air stream where it is dissipated and the original conditions of the flow are resumed.

The theoretical picture of air movement over a shelterbelt has been described by Nägeli (1943), Geiger (1951), Kreutz (1952b) and Gloyne (1954). An air "cushion" with a low wind speed is built up on the windward side of the belt (Nägeli 1943). This cushion stretches in a smooth line from the ground to the top of the belt and the greater part of the hitherto horizontal air stream climbs up the smooth slope of this cushion. Some of the air stream passes through the air cushion and through the shelterbelt at a more or less undisturbed level. In the flow over the shelterbelt there is a pronounced acceleration compared with the speed of the uninterrupted wind in open conditions away from the belt. Above the top of the shelterbelt there is another air cushion of very small dimensions (Marczell 1926) and above this there is rapid acceleration as the speed is conditioned by the compression of the air stream which has been forced to climb. The most extensive air cushion is on

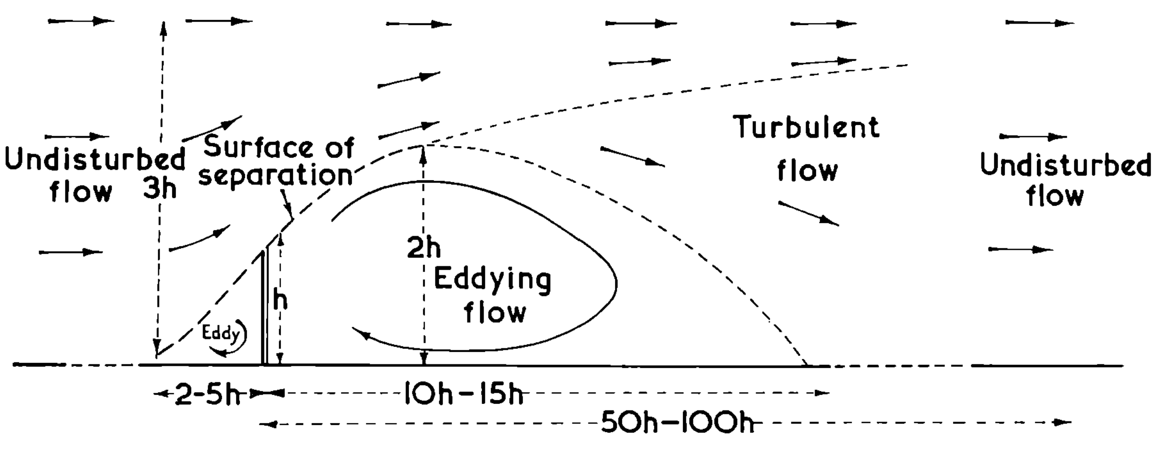


FIGURE 2. Some characteristics of the air-flow pattern due to a near-solid, cross-wind barrier (not to scale) (after Gloyne).

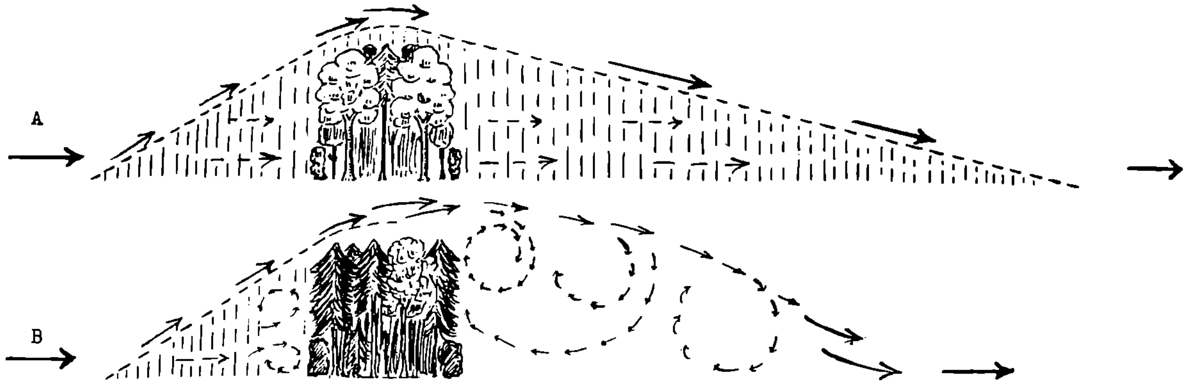


FIGURE 3. Flow of wind over (A) a moderately penetrable and (B) a dense shelterbelt.

the leeward side, the upper margin sloping gradually from the top of the belt to the ground. As on the windward side and above the trees of the shelterbelt, there is an increase in the speed of flow immediately above the cushion (Fig. 3, top).

These conditions obtain where the wind is forced to overcome the shelterbelt, partly by penetration, largely by rising over the top and partly by circumnavigating it. In such cases there is no significant eddying, as is found with impenetrable barriers. Instead of eddies, there occurs around the belt a relatively windless zone, the scale of which depends on the structure and height of the belt.

When a windbreak is completely impenetrable to the wind, practically the whole of the force of the wind has to be deflected upwards and over the barrier. There is a certain amount of loss of kinetic energy due to collision of the air molecules with the barrier itself or with the cushion of air which has developed on the windward side. This cushion or concentration of pressure causes the upward deflection of the air stream to take place at some distance in front of the barrier in much the same way as with a penetrable obstacle. However, the pressure behind the barrier is low, due to the fact that no wind passes through the barrier to form a leeward air cushion. Consequently, a suction effect occurs and the air currents above the windbreak are drawn downwards, thereby causing intense turbulence to leeward. This is shown diagrammatically in Figs. 2 and 3 (bottom). The different eddy areas behind penetrable and impenetrable barriers have been demonstrated by Finney (1939), (Fig. 4).

An impenetrable barrier therefore causes the wind to resume its normal velocity and pattern at a comparatively short distance from the obstacle. Although it is doubtful that even the most dense shelterbelt can be considered an impenetrable barrier in the sense of a solid wall, it is certain that fairly intense turbulence takes place and is often responsible for damage to crops on the leeward side of a belt which is practically impenetrable to the wind. In the case of the barrier or belt which is partially penetrable there is a more gradual tendency for the streamline flow over the barrier to re-establish its unobstructed pattern and the sheltered area is correspondingly longer in extent. The isotacks, lines of equal velocity of the wind, in the vicinity of open and dense artificial screens with an unobstructed wind speed of 5 m/sec are shown in Fig. 5.

The Sheltered Area

The extent of the sheltered area depends chiefly upon the degree of penetrability and the height of the shelterbelt or barrier. In elevation, the zone of reduced velocity extends for a short distance above the barrier, as shown in Figs. 3 (top) and 5, and has been confirmed by Hallberg (1943) in his investigations of streamlines. In the study of a dense hedge, 1.68 m in height, Rider (1952) found that, at a height of 2.0 m, a slight reduction of the wind velocity with respect to the open ground wind could still be observed.

The shape of the protected area when the wind strikes the shelterbelt at right angles is illustrated in Fig. 6. From experimental study of windbreaks composed of 6-inch boards, with 12-inch spaces in the lower half (representing the trunk space) and 3-inch spaces in the upper half (representing the crown space), Bates (1944) found that a wind of 20 mi/hr was reduced over a distance equal to 30 times the height of the barrier, a quarter of the protected area being on the windward side and three-quarters on the leeward side. The lowest recorded velocity was 47 per cent of the free wind velocity. When the wind strikes the shelterbelt obliquely, the extent of the shelter, measured perpendicular to the belt, is correspondingly shorter (Gorshenin 1941).

Effect of Height of the Shelterbelt on the Sheltered Area

Expressed in multiples of shelterbelt height (h), the zone of wind velocity reduction on the leeward side of the belt may extend to about 40 or 50h before incident flow is re-established (Gloyne 1954). Effects have been identified at 100h or more (Bodrov 1935) but this would appear to be unusual; in any event, effects beyond 40h are unlikely to be of practical consequence.

Results of early investigations reviewed by Denuyl (1936) are varied. In Russia, wind reduction has been found to extend to over 20-30h to leeward (Leontievsky 1934); to 10-15h (Goviadin 1933); to 20h (Vyssotsky 1929); to an effective distance proportional to the square of the height of the belt (Pianitsky 1932). When discussing the effect of the height of the shelterbelt on its sheltering influence, Gorshenin (1934) assumed from data produced that this influence extended to 30-40h but used 25h as a basis for calculations. In a later paper (1941) he decided that the sheltered distance might be reliably expressed as 30h but that the sharpest reduction in the wind velocity extended to only 10-15h. Values

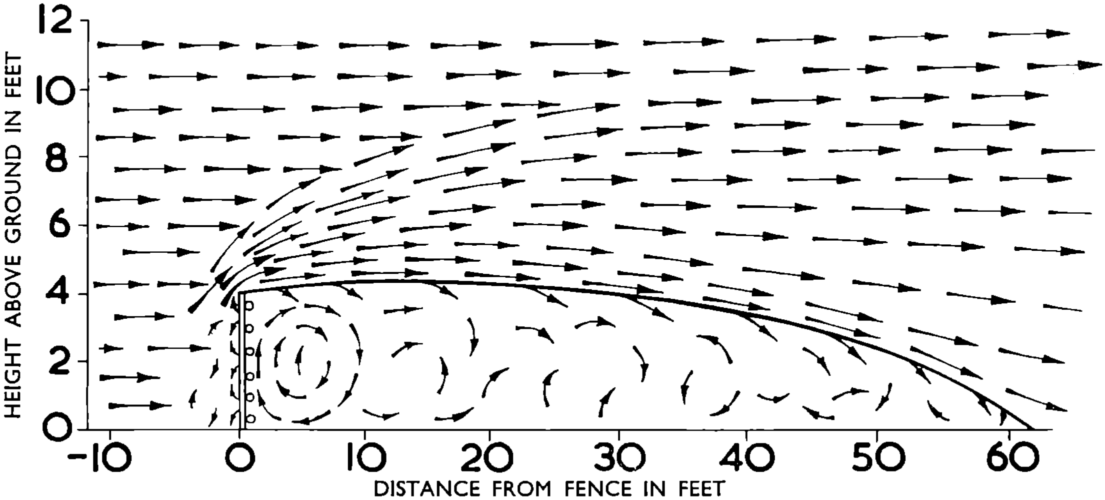


FIGURE 4a. Eddy area behind a permeable four foot high vertical slat fence, of 50 per cent density, (after Finney).

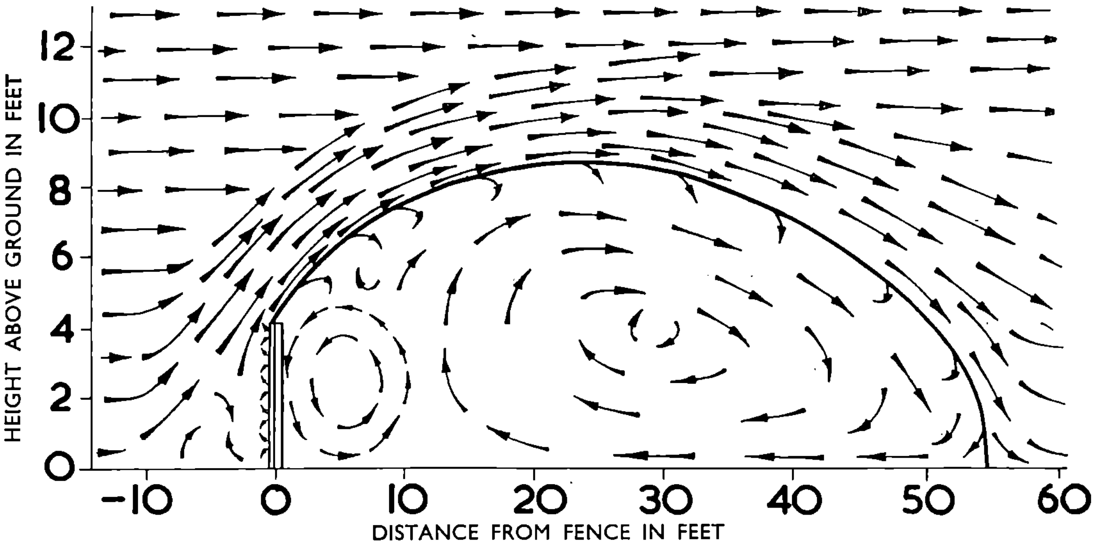


FIGURE 4b. Eddy area behind an impermeable four foot high solid fence, of 100 per cent density, (after Finney).

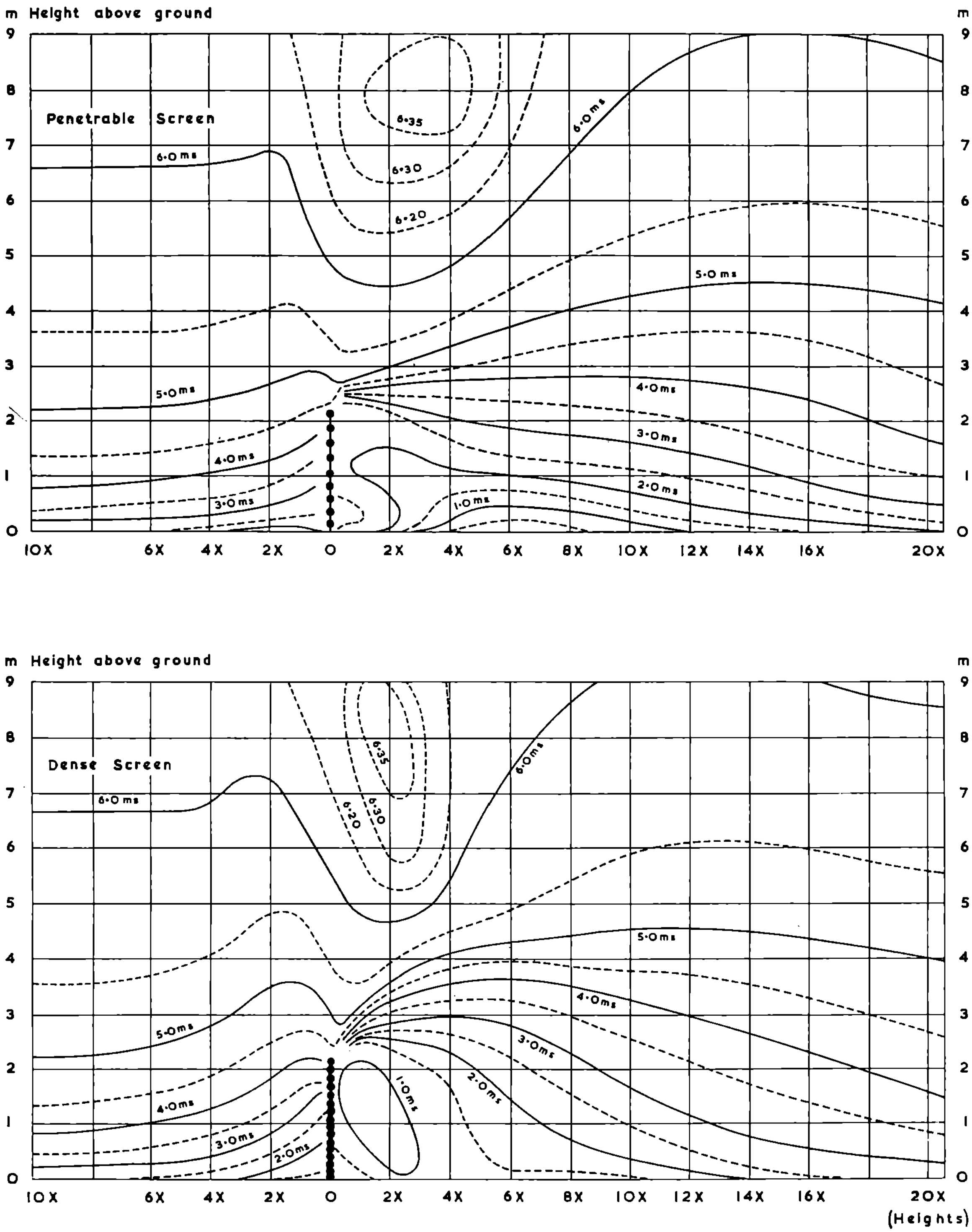


FIGURE 5. The course of lines of equal wind velocity (isotacks) in the vicinity of penetrable and dense reed screens with a free-wind velocity at 2.2m above ground of 5 m/sec. (ms = metres per second) (after Nägeli).

recorded by workers in other countries include the following: in Norway, 12h (Barth 1934); in Denmark, 10h but favourable effects traced much farther away (Flensborg 1926); in Australia, 6-15h (Anderson 1931); in U.S.A., 20h (Cheyney 1931) and 10h, with practically no effect at 20h (Bates 1911, 1934), and complete protection over 5-6h (Metcalf 1930).

More recently, Rhodesian experiments have shown a leeward protected zone extending to 10-20h and to 2-5h on the windward side (Pardy 1946, 1949); a particular shelterbelt reduced the wind velocity over 13h in Australia (Sims 1945) and in New Zealand complete shelter has been expressed as extending to 5h and partial protection to 15h (Syme 1944). Velocities recorded behind an artificial windbreak in Japan at distances of 10, 20 and 30h were 61.44, 69.33 and 77.44 per cent respectively of the wind speed in the open (Iizuka 1950).

As a result of investigations in Switzerland, Nägeli (1943) states that the shelter-effect of a belt is noticeable for 5-7h to windward and 25-30h to leeward. In later studies of 12 different types of shelterbelts (1946) he found that the average distance at which protection began on the windward side of the belt was 9h, never more than 10h or less than 5h,

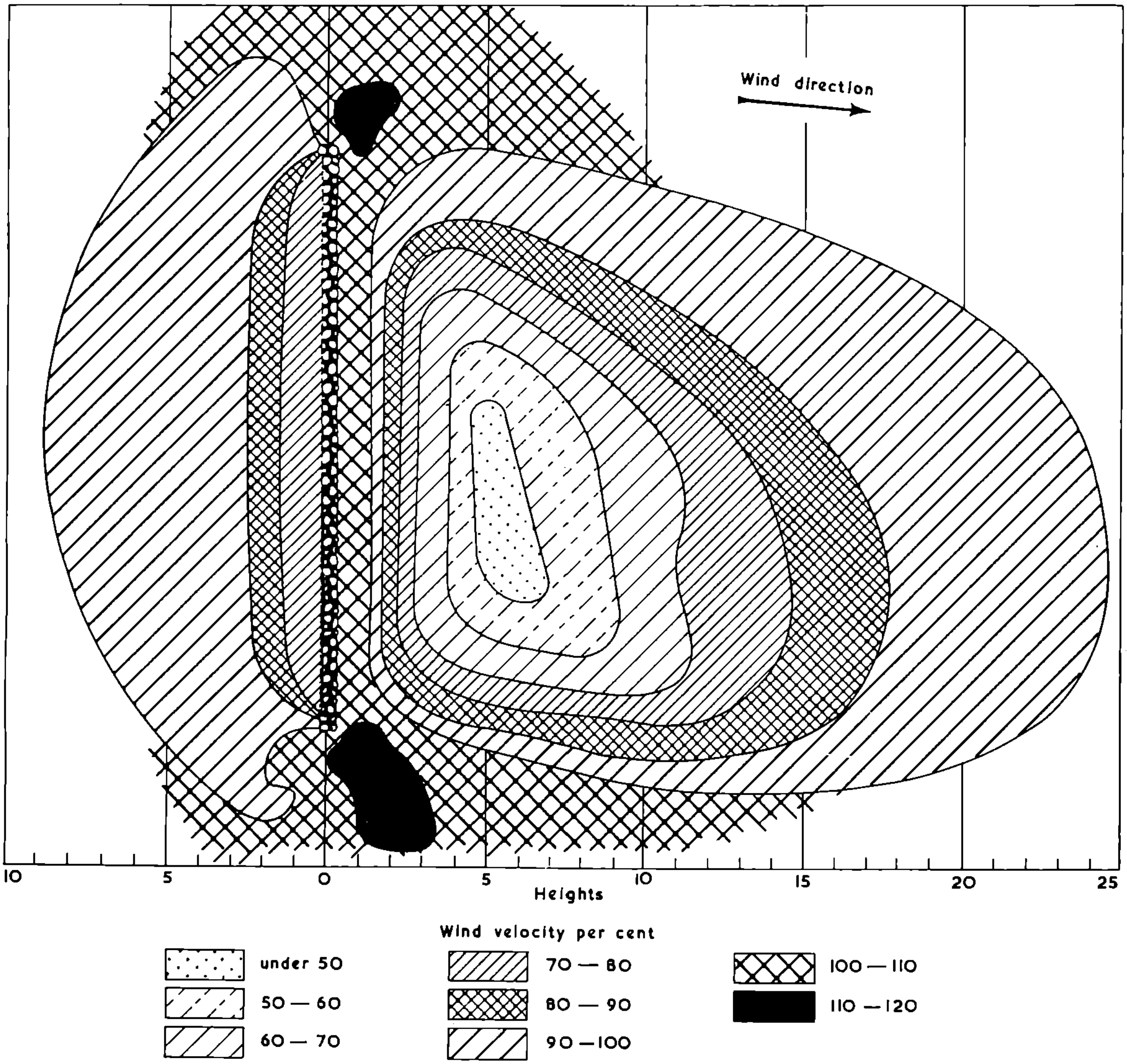


FIGURE 6. Zone of wind velocity abatement near a windbreak of moderate penetrability, (after Bates).

and it extended to leeward for an average of 30h, seldom more than 35h, never more than 40h or less than 20h.

Summarising, the sheltered zone to leeward of a shelterbelt may be considered to extend to approximately 30 times the height of the belt but, if a 20 per cent wind reduction is taken as the criterion of useful shelter, this may be said to extend up to 15 or 20 times the height of the belt. Different opinions have been expressed regarding the minimum wind speed reduction which should be considered significant. This must depend to a great extent on the wind speed prevailing in the unsheltered area and also on the critical velocity values above which soil erosion occurs or plant growth is inhibited. With high velocities a much smaller reduction than 20 per cent may be significant.

Variation in the experimental results recorded above may be ascribed chiefly to:

(i) differences in width and cross-sectional profile of the shelterbelts examined,
(ii) differences in degree of penetrability to the wind,
(iii) differences in wind direction and velocity at the time of measurement,
(iv) differences in experimental methods, in the height of measurement above ground and in the plant cover of the research areas.

Effect of Penetrability of the Shelterbelt on the Sheltered Area

Nägeli (1946) records remarkable similarity in reductions of velocity caused by 12 different shelterbelts (Fig. 19) and concludes that the shelter-effect is determined almost entirely by the height of the belt. However, the divergence between the curves of relative velocity is sufficient for the belts to be grouped into four density classes—open, moderately penetrable, dense and very dense (Fig. 7). The abatement of the velocity follows the same pattern on the windward side of the belts but differences become more marked on the leeward side. Similar results have been obtained by Panfilov (1936) as shown in Fig. 8 where:

Structure I = shelterbelts open throughout their height (partly permeable to wind)
Structure II = shelterbelts dense throughout their height (impermeable to wind)
Structure III = shelterbelts of medium density (slightly permeable) below and dense above
Structure IV = shelterbelts of medium density above and open below.

It has been stated that the extent of the sheltering influence is directly proportionate to the density of the shelterbelt (Denuyl 1936) but this is contrary to general opinion. Turbulence increases with density (Bodrov 1936) and the dense shelterbelt, although providing a greater degree of shelter immediately to leeward, gives a comparatively restricted zone of effective shelter, since the air stream, rising over the belt and meeting a high velocity above the trees, is forced down to the ground again at a short distance from the belt. The shelterbelt which allows wind to permeate through it at a reduced velocity causes a lower degree of shelter behind the belt but this effect extends over a considerably greater distance. The resumed acceleration of the wind is more gradual and therefore less harmful (Figs. 4, 5, 7 and 8). Thus a shelterbelt of moderate penetrability to the wind provides the most effective shelter (Nøkkentved 1938, 1940; Gorshenin 1941; Nägeli 1943).

On the basis of wind-tunnel studies, the optimum degree of penetrability of a shelterbelt has been recorded as 48 per cent, i.e. with 48 per cent of the windbreak frontal surface open, the openings being uniformly distributed over the whole surface (Nøkkentved 1938; Blenk 1952). Later Danish wind studies show that, independent of the turbulence of the free wind, the optimum geometric penetrability is 35 to 40 per cent (Jensen 1954). Konstantinov (1951) quotes a penetrability to the wind of about 30 per cent in the case of natural shelterbelts; such belts act as a "lattice" and the turbulence of air currents striking them breaks up and diminishes.

Effect of Variation of the Free-wind Velocity on the Sheltered Area

Discussing density of shelterbelts, Gorshenin (1946) remarks that with dense belts the protective efficiency immediately to leeward increases in direct proportion to increasing free-wind velocity but, at a distance of 10h, this relationship vanishes. On the other hand, with belts penetrable near the ground and "latticed" (see *Glossary*, page 000) in their middle part, the effectiveness close to the belt increases inversely with the wind speed but, beyond 10h, the reverse applies, i.e. the wind-protective influence increases with higher wind velocity in the open.

Increased shelter-effect with increased free-wind velocity has been mentioned frequently. Wind measurements made over a 30-year period from 1887, during which period a spruce belt was planted, show a reduction of 30 per cent in the wind velocity, rising to 47 per cent in heavy gales, when the belt reached an effective height (Geiger 1931). Denuyl (1936) was of the opinion that the sheltering influence of a barrier would be reduced when the wind velocity increased. However, Bodrov (1936) pointed out that, under the influence of shelterbelts, turbulence is increased, the horizontal and vertical components of the velocity of the air currents becoming decreased and increased respectively; such changes are more marked the higher the velocity of the open-ground wind.

The distinct reduction of penetrability in a spruce belt with increased wind velocity has been ascribed to the fact that spruce branches act in a manner similar to slats in a Venetian blind (Woelfle 1939). It may be supposed that the nature of the free wind has some influence on velocity reduction in the vicinity of a shelterbelt and there must be a definite value of the velocity, at which the relative protection in sheltered areas reaches an optimum level; a row of trees, being somewhat elastic, will change its form according to the prevailing wind speed, thereby affecting the resistance to the wind and the degree of penetrability (Nägeli 1946). Bates (1944) has concluded that both the depth, expressed by percentage of velocity reduction, and the width of the pool of quieted air will increase as winds become stronger and the centre will tend to move a little further away from the windbreak.

In practice the main features of the pattern of air flow are found to be similar for wind speeds from 5 to 25 mi/hr (Gloyne 1954) and the eddy area, defined as the cross-sectional area enclosed by a barrier, the ground and the line where the air speed is zero, remains constant for any height of barrier and any wind velocity up to 30 mi/hr (Pugh 1950). In wind-tunnel studies made in America (Woodruff and Zingg 1952), it was observed that the percentage velocity reduction attributable to placement of a barrier is constant at a given location in the vicinity of the barrier, irrespective of the unobstructed velocity. It follows that complete protection or benefit should be based on reduction of the velocity to a value less than the critical value for soil or plants; therefore, the higher the wind velocity, the less the absolute benefit of a windbreak.

From this evidence it would appear that the relative shelter-effect behind a rigid barrier remains more or less the same for varying speeds of the wind but that, where the barrier changes its form according to the wind pressure to which it is subjected, as in the case of tree crowns, the penetrability or vertical structure of the barrier will be affected and the zone of reduced velocity altered accordingly. A shelterbelt, normally of moderate penetrability, may become more impermeable in high winds and, similarly, a too open belt may give a more effective degree of shelter. However, it seems probable also that the sheltering efficiency of a belt is reduced when turbulence of the free wind is increased, as when the wind passes over a very rough surface before it

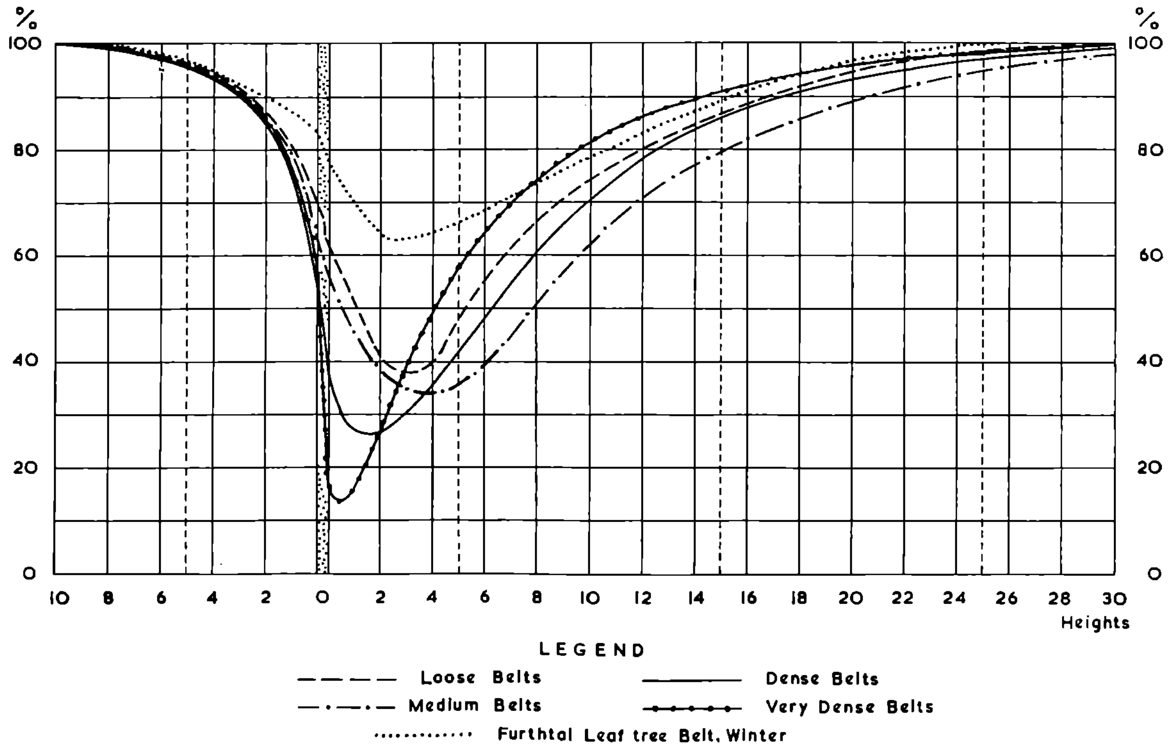


FIGURE 7. Relative wind velocities in the vicinity of Swiss shelterbelts of different degrees of penetrability, (after Nägeli).

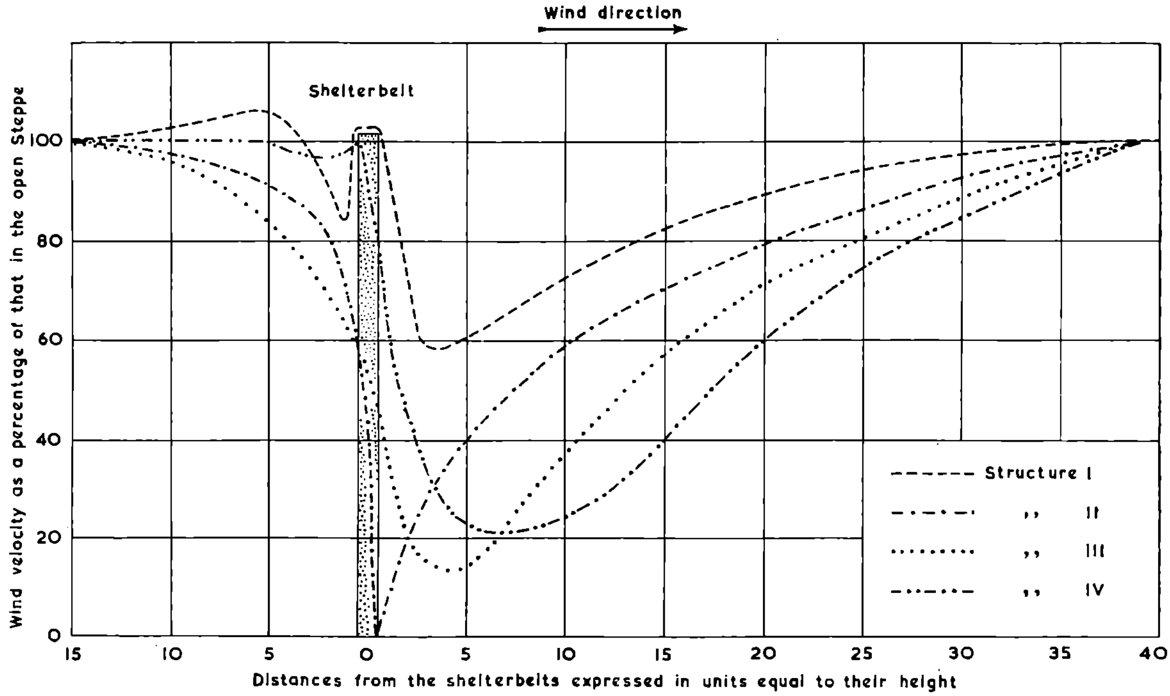


FIGURE 8. Relative wind velocities in the vicinity of Russian shelterbelts of different structure, (after Panfilov).
Structure I = shelterbelts open throughout their height (partly penetrable to wind)
Structure II = shelterbelts dense throughout their height (impenetrable to wind)
Structure III = shelterbelts of medium density (slightly permeable) below and dense above
Structure IV = shelterbelts of medium density above and open below.

strikes the belt (Jensen 1954). The character of the free wind is therefore important.

Effect of Width of the Shelterbelt on the Sheltered Area

The field of shelter-effect depends primarily on the height and penetrability of the shelterbelt. Width of the belt is a secondary consideration in so far as it affects the degree of permeability only; width exerts a negligible influence on the velocity abatement but can cause notable variation in the microclimate of the sheltered area. Such variations are slight in the usual run of shelterbelts, the exception being for evaporation, but they become important in the case of plantations (Nägeli 1946). In practice, the width of shelterbelt employed has been determined by the area of land which could economically be devoted to planting and the minimum number of tree-rows necessary to maintain optimum penetrability.

Studies of the influence of width have been made in connexion with the extent of shelter on forest margins. Nøkkentved (1940) discovered that there is a more extensive sheltered zone on the leeward margins of plantations which were more than 2,000 m wide than occurs with plantations less than 2,000 m in width. In the former group of plantations studied, the sheltered area extended to 60-70h and, in the latter, to 30-40h. This phenomenon was assumed to be due to the extent of the plantations in the direction of the wind and to arise from two causes:

(a) the flow of air over the tops of the trees becoming stabilized in a horizontal direction so that, on leaving the leeward edge of the forest, it merges only very slowly into the sheltered area, and
(b) the retarding effect or frictional drag exerted by the forest canopy on the air stream extending to a greater height in the atmosphere than occurs with a low plant cover or a narrow shelterbelt; so that the normal ground wind is "lifted into the air" and it is some time before it reaches ground again.

The minimum width of plantation considered in these investigations was 200 m and in this case a wind speed of 60 per cent of the free wind velocity was attained at a distance of 7.5h to leeward of the plantation. The values for the extent of shelter are in general agreement with the findings of Marczell

(1926) but greater than those obtained by Woelfle (1939). However, it was emphasised that the Danish investigations were preliminary and no general conclusions could be drawn from the results; difficulties were encountered in obtaining measurement points for the unobstructed wind velocity.

These studies have been developed (Jensen 1954) and compared with model-scale tests in a wind-tunnel. It appears that the shelter effect behind woodlands must increase with the extent of the wood in the direction of the wind, but in cases where the width/height ratio is of an order of magnitude of more than 50 the increase is insignificant. On the whole, the sheltered distances found with the model tests were shorter than those obtained under natural conditions by Nøkkentved but this might presumably be attributed to the fact that the air current in the wind-tunnel was more turbulent in character than the wind in nature.

The Danish results are at variance with those obtained by Nägeli (1946, 1953b) in field experiments and by Blenk (1952) in wind-tunnel research. Measurements made with a coniferous plantation (Nägeli 1953b) with a width, near the measurement line, of 600 m show a reduction in wind velocity from 100 per cent at 9h to windward of the forest to 62 per cent at the windward edge and a minimum of 11 per cent within the plantation. The velocity rises again to 22 per cent at the leeward edge, to 50 per cent at 1h and 96 per cent at 30h. Comparison with values for a shelterbelt of similar density but only 20 m wide (Fig. 9) shows little difference to exist on the windward side; inside the 20 m belt the wind speed remains at least 33 per cent above that in the forest but leeward speeds are lower for about 20h. These studies, together with velocity measurements obtained in an orchard (Nägeli 1946), show that with a wide sheltering object the minimum velocity occurs within the object and therefore the wide shelterbelt or forest block consumes its own shelter to some extent.

Pfeiffer (1938) pointed out the lifting of the air stream before a forest and the downward spread of turbulence in the leeward zone. On the basis of tunnel investigations with model-scale shelterbelts having widths of 1.7h and 10h respectively, Blenk (1952) records the much earlier resumption of wind velocity behind the wide woodland strip and suggests that this behaviour may be explained by the fact that the wide belt leads the wind parallel to its crown surface, after which it comes down to ground level very quickly on leaving the leeward edge. The wind over an isolated, impenetrable barrier has an ascending tendency, a more gradual re-establishment of the normal flow pattern occurs and it is more effective therefore than the wide shelterbelt. These observations were confirmed by experimental study of stream flow in a small water-tunnel and are shown diagrammatically in Fig. 10.

Japanese investigations of the width of windbreaks, made with model trees in the field and also in

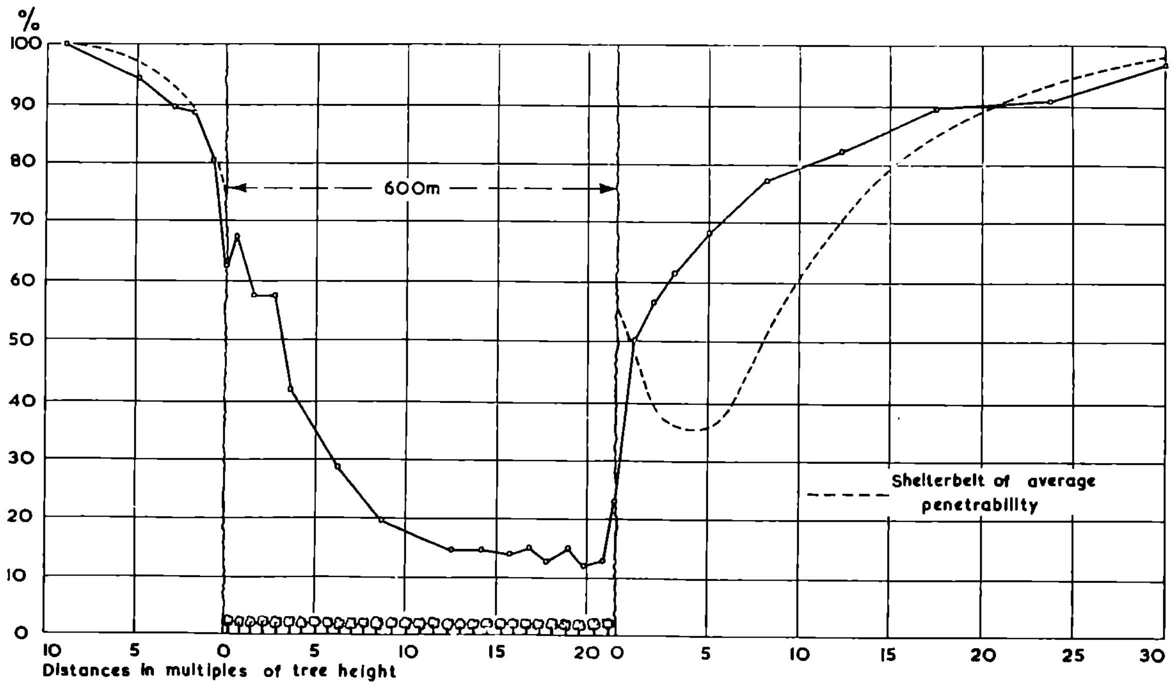


FIGURE 9. Relative wind velocities in the vicinity of a large forest complex, (after Nägeli).

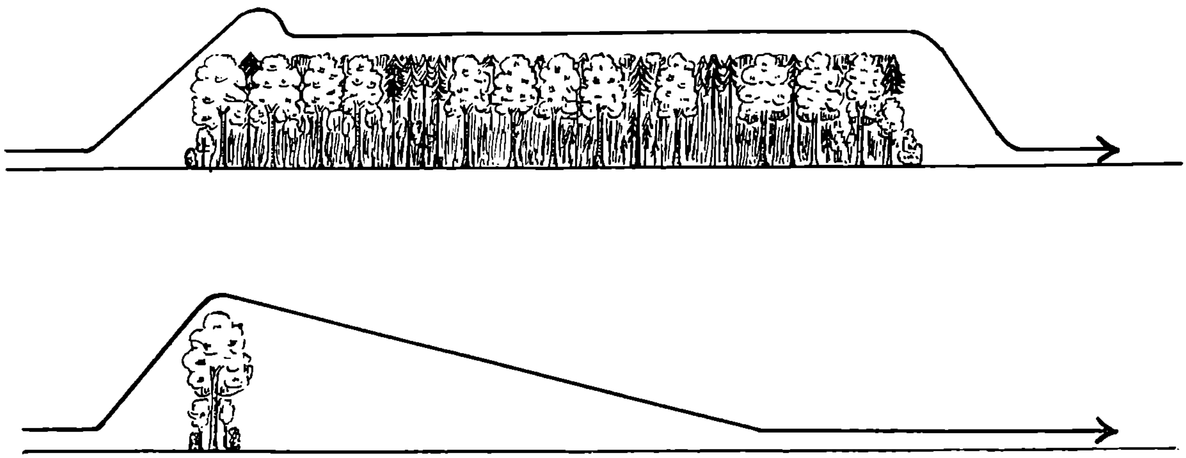


FIGURE 10. Diagram of wind flow over a forest block and a narrow shelterbelt, (after the investigations of Blenk).

the wind-tunnel, show that the resistance offered by the shelterbelt has greater dependence on the sum of the tree diameters at breast height than on the average diameter (Iizuka 1952). The practical significance of these studies is obscure.

Effect of the Cross-sectional Profile of the Shelterbelt on the Sheltered Area

The streamlining of belts so that in cross-section they appear as a gabled roof with a wide sweep at the eaves has been suggested, this being achieved by planting central rows of the main tree species, flanked on either side by smaller trees and shrubs (Bates 1934). Wind-tunnel studies of the effect of the number of rows within a shelterbelt and their general design and orientation with respect to the prevailing wind have been made with models of 5-row, 7-row and 10-row belts as illustrated in Fig. 11 (Woodruff and Zingg 1953). Relative velocities were recorded at the ground surface and at elevations extending to three times the height of the tallest trees. Velocity ratios, U_t/U_c, where U_t is the velocity in the wind-tunnel with the shelterbelt in position and U_c the corresponding velocity in a clear tunnel, are shown in Fig. 12.

In the zone between 0.1h and 3.1h above the ground surface, the following order of effectiveness was established:

(1) 10-row shelterbelt, design C, which did not create as large a zone of accelerated flow above and behind the belt as in other cases;
(2) 5-row belt F, which showed a zone of comparatively low velocity reduction near the margin, due to the smaller density ratio and the consequent "jetting" of air between the trees;
(3) 10-row belt B;
(4) 7-row belt E;
(5) 10-row belt D (design C reversed);
(6) 10-row belt A (design B reversed).

With regard to surface protection against wind erosion, the order of effectiveness was found to be as follows: C, A, D, B, E, F. The conventional design of shelterbelt for American conditions, represented by the model C, proved to be most effective at both levels; the belts of 5 and 7 rows offered nearly as much protection as the 10-row design and showed greater efficiency per tree. It would appear that these results should be accepted with reservations since the natural tree cannot be simulated effectively on a model scale and the reversal of the models shown in Fig. 11 would doubtless involve changes in the degree of penetrability to the wind and not merely in the one variable of cross-sectional profile.

It may be assumed, from basic principles of aerodynamics, that a shelterbelt, which in cross-section approaches an aerofoil, would offer the minimum resistance to the wind and the zone of shelter produced would be small.

In connexion with the cross-sectional profile of a shelterbelt, mention should be made of experiments made by Nøkkentved (1932), quoted by Goldstein (1938), with a model house having a high roof slope. It was observed that, when the wind-tunnel air stream was switched off, the eddies to leeward of the roof gable were in reverse rotation to when the current was flowing uniformly. This accounts for trees on the leeward edge of a wood being uprooted, especially in a gusty wind. It follows that this phenomenon would be more pronounced in the case of a dense shelterbelt.

Effect of Length of the Shelterbelt on the Sheltered Area

Considering the protection afforded by an E-W shelterbelt against winds varying between SE and SW, a triangle to the North of the belt will be continuously sheltered. Until this triangle extends to 12 times the height of the shelterbelt, the full possibilities of distance protection are not being utilised; this involves having the belt 24 times as long as it is high (Bates 1944). For protection against winds always normal to the belt, length would require to be 12 heights only.

Results of investigation of the field of protection afforded by screens (Fig. 13), show that the lines of equal wind velocity (isotacks) have a tendency to deviate towards the centre of the barrier and to adopt a course parallel to it. An extension of the barriers would have changed nothing of the diagrammatic illustration except that the zone of isotacks parallel to the screens would have been widened. Thus, the experimental belts were just long enough, with respect to their height, to produce the greatest possible shelter effect, at least in their centre. The ratio of height to length in this case was 1:11.5. In the same proportion, natural belts of 20 m in height should have a length of 230 m in order to obtain the maximum shelter effect in their centre; any extension of the belt beyond this length may be considered as producing a gain in protected area (Nägeli 1953a).

Wind Conditions at the Extremes of the Shelterbelt

Increased wind velocity, higher than that in the open, occurs at the ends of shelterbelts and screens (Figs. 6 and 13), due to air currents sweeping round the belts. Smoke experiments have confirmed this feature (Kreutz 1950; Woelfle 1938). These zones are small in relation to the length of the shelterbelt. In the immediate vicinity of the end of a screen, on the leeward side, a marked concentration of lines of equal velocity is apparent, as shown in Fig. 13, particularly in the case of a dense screen; these conditions are analogous to those of flow over the

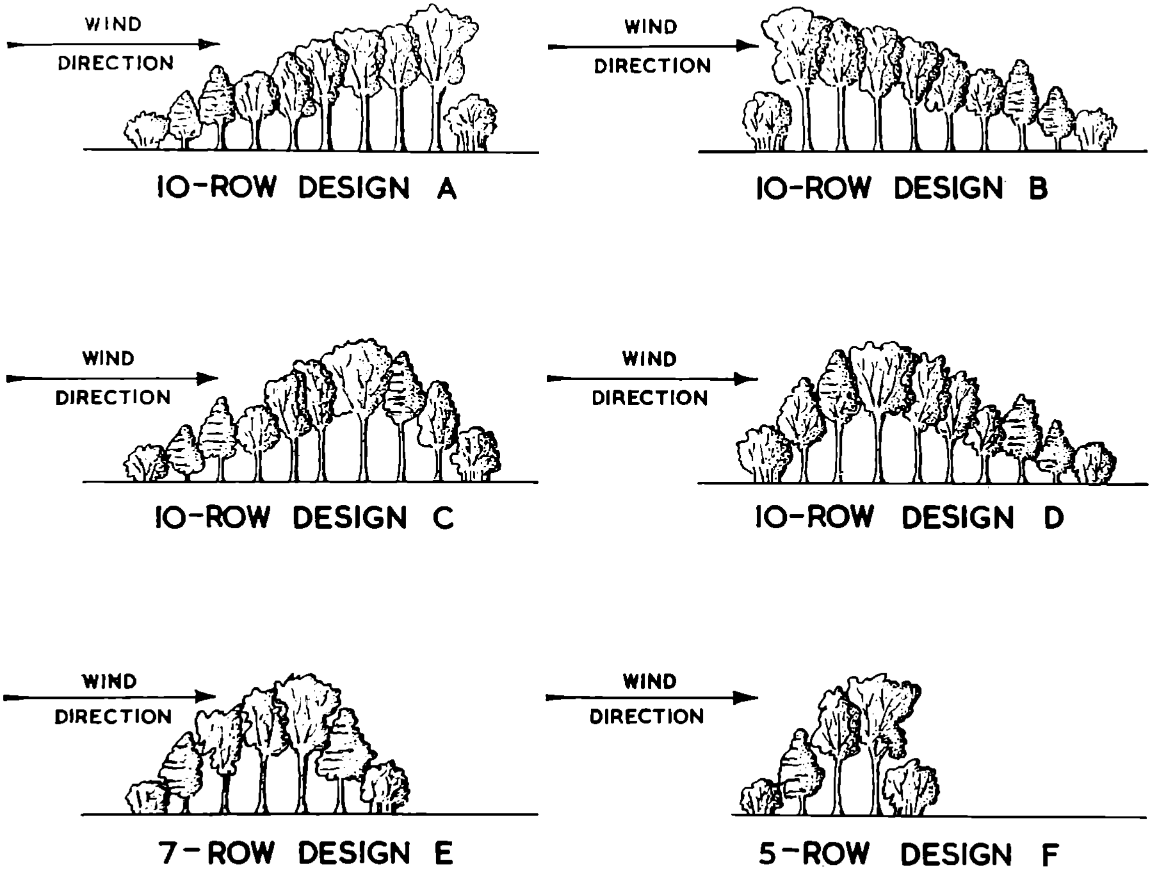


FIGURE 11. Diagram of orientation and number of tree rows in the shelterbelt models used in American wind-tunnel investigations, (after Woodruff and Zingg).

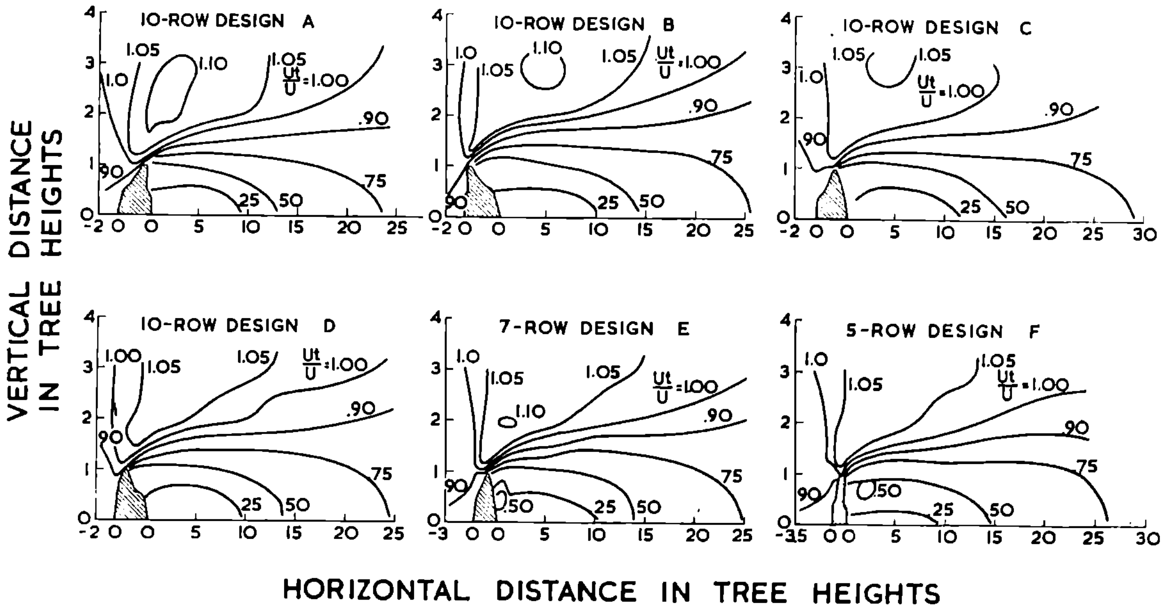


FIGURE 12. Velocity ratios U_t/U_c obtained in the vicinity of the models shown in Figure 11, (after Woodruff and Zingg).

obstacle. Whilst this phenomenon is of little practical importance when it occurs above the screen, it may harm and reduce growth as soon as it takes place at the level of crops being protected, especially since this zone of increased velocity is displaced constantly through the free wind changing its direction slightly but with rapid frequency (Nägeli 1953a).

Fig. 13 shows also that the leeward sheltered zone is not confined within lines drawn perpendicular to the ends of the barrier but is broader, parallel to it, than the barrier is long.

Effect of a Gap in the Shelterbelt

Frequent gaps in shelterbelt systems are advocated in the Russian literature, particularly where belts intersect one another. With a gap of 12 m in width, although a zone of increased velocity develops within the gap (Fig. 14), there is practically no lateral extension of this "draught zone" and at a short distance from the gap the wind abatement is normal (Nägeli 1946, 1953a).

Similar findings have been made by von Elmern (1951). A velocity of 3.6 m/sec was observed in the open and of 4.5 m/sec within the gap.

Deflection of the Wind by the Shelterbelt

The wind, such as blows across a region free from obstacles, is deviated by a shelterbelt into a direction more parallel to the border of the stand (Woelfle 1935, 1936). However, when the air current enters a belt or forest stand, it is deflected more or less normal to the margin (Woelfle 1939). Pronounced deviations and consequent turbulence are only produced in the fields of influence of very dense belts (Nägeli 1946).

Variation of Wind Velocity in the Vertical Plane due to the Shelterbelt

By experiment, Nägeli (1946) found that at 1.4 m above ground, the height of his general field measurements, this point was already outside the zone of strong variation due to frictional disturbances caused by the ground surface. In later studies (1953a) velocities were measured at 9 elevations between ¼ and 4 times the height of artificial barriers. Fig. 15 shows that the protective effect of a windbreak is not greatly diminished until the height of the obstacle, if the latter is dense, and the position and percentage value of the minimum velocity remain relatively unchanged. In the case of a penetrable screen, a distinct diminution of the protective effect appears at the height of the barrier but the zone of shelter is more pronounced. This evidence may explain the significant improvements in crop yields behind windbreaks relatively short in size, such as low screens or rows of maize (Kreutz 1952b), and in orchards behind shelterbelts which are not appreciably higher than the fruit trees.

In Fig. 15 a secondary maximum velocity occurs in place of the minimum on the leeward side beyond

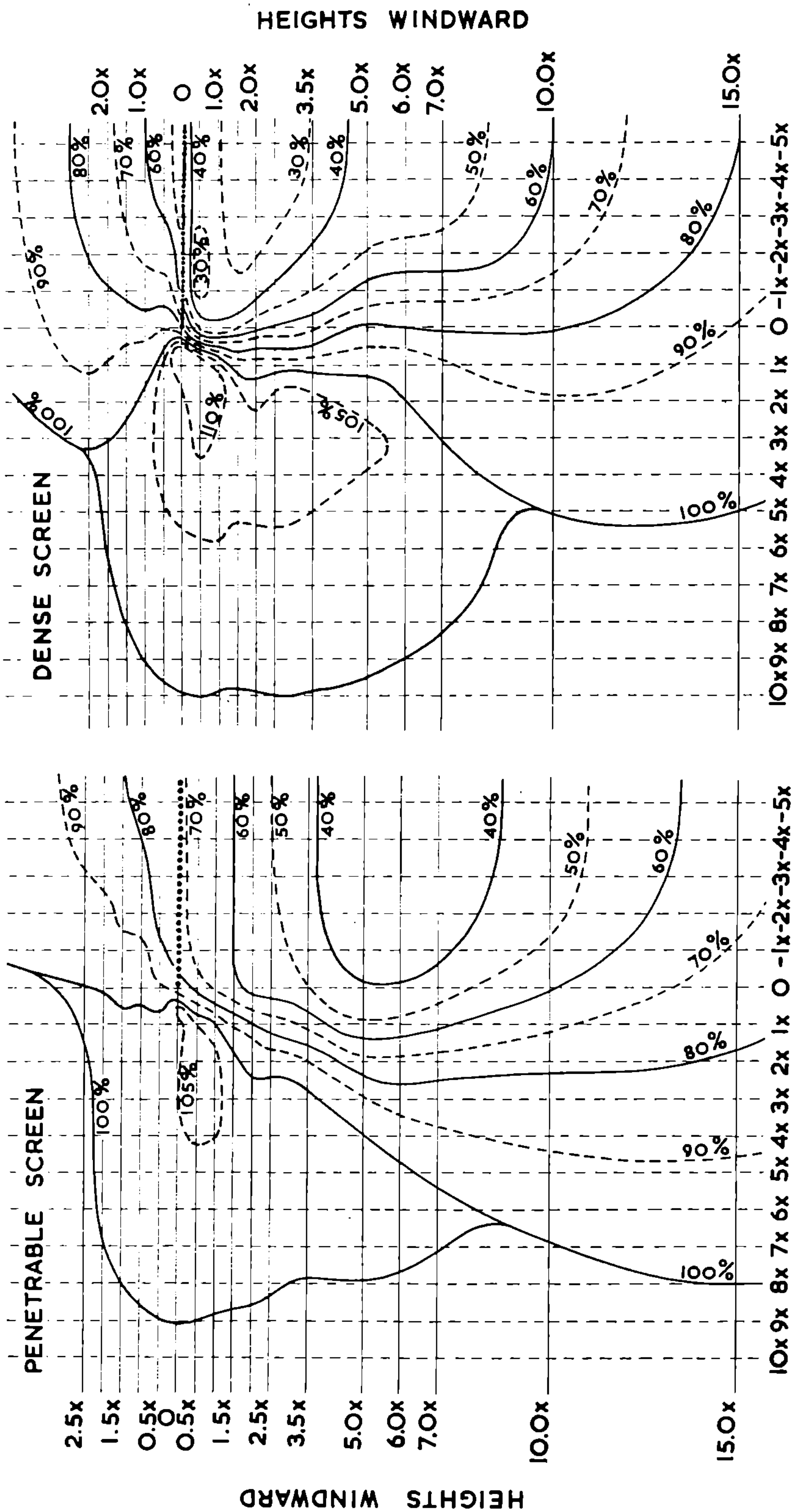


FIGURE 13. Plan of wind velocity abatement by penetrable and dense reed screens. (Height of measurement, 0.55m = ¼h), (after Nägeli).

a height of $1\frac{1}{2}$h (3.3 m) above ground and a small abatement of the wind speed takes place after this maximum. At four times the height of the screen the influence of the windbreak in a vertical direction has not yet reached its upper limit, which explains the comparatively long horizontal projection of the moderating influence at lower elevations.

Fons (1940) investigated wind speeds at heights up to 142 ft. over grassland, forest and brush sites, but his results are of little importance from a microclimatic point of view.

Effect of Shelterbelts on Wind Erosion of the Soil

One of the principal uses of shelterbelts from a universal aspect is the control of wind erosion of the soil. Mention has been made of the wind-tunnel studies by Woodruff and Zingg (1953) regarding the degree of protection at the soil surface afforded by different model shelterbelts, and a considerable amount of literature is available on the dynamics and control of wind erosion.

By using a special soil-catcher, Iizuka (1950) has observed that a windbreak, which reduced wind velocities to 61, 69 and 77 per cent of that in the open, at leeward distances of 10h, 20h, and 30h respectively, decreased the soil-blowing effect to 0.14, 18.04 and 50.54 per cent correspondingly.

Quantities of dust, blown from a road adjoining a dense shelterbelt and measured at several points behind the shelterbelt, have been found to be proportionate to the wind speed at these points; with the increase of turbulence behind the belt, the carrying capacity of the air decreased and the dust settled (Hennebo 1952).

In a survey of soil erosion in Eastern England (Sneesby 1953), during which areas affected by a serious "blow" in spring were examined, 10 shelterbelts showed an average protection for 14h, the maximum sheltered distance being 27h. Two mixed plantations, 220 and 250 yds wide and 30-40 ft. and 50-60 ft. high respectively, sheltered distances of 300 yds; in the latter case the ground sloped away from the damaging wind. Thick hedges showed a protected zone averaging 27h, whilst solid windbreaks were reported as having an average sheltered area of 17h. Causes of soil blowing are recorded as an open, or virtually open, land surface, where the soil has been broken down by frost and cultivation into a fine tilth and whose surface has dried out to become a dust and, secondly, a gusty wind.

Effect of Physiography on the Sheltered Area

By analysis of anemometric measurements, protective belts of trees on arable slopes have been found to have no less sheltering efficiency than on level plateaux (Gorshenin 1946). Air currents near the ground are roughly parallel to the topography but with increasing velocity as the degree of slope increases, although Panfilov (1940) denies that there is an increased velocity on the upper parts of slopes except in places of sharp transition from one form of relief to another. D'Yachenko (1946) has confirmed that the velocity of a wind blowing up a slope increases towards the brow, whereas downwinds decrease progressively in velocity, but these changes may be slight. This involves a considerable acceleration or deceleration of speed respectively, the speeding-up or slowing down factor depending on the steepness and roughness of the windward slope (Andersen 1954). With acceleration, values of 150 per cent of the normal velocity may be reached but generally are below 125 per cent (Putnam 1948).

The connexion between topography and wind pattern has been studied from various aspects. An isolated hill, which is relatively high compared with its horizontal extension, tends to be by-passed by the wind rather than overflowed (Geiger 1927-9). The maximum wind velocities occur on the flanks of the hill, a marked minimum at the lee, and a secondary minimum at the windward side. Canalisation of the wind by valleys is often connected with a change in direction and locally with an acceleration in speed and plays an important part in exposure (Andersen 1954). Leeward slopes below 8° are assumed to be unprotected (Woelfle 1950) and it is assumed that the sheltered zone behind the summit of a hill is restricted to a short distance, according to the steepness of the slope, and is followed by a region with increased wind speeds (Woelfle 1937); this may be interpreted as the effects of increased turbulence and changes in the vertical gradient of the wind.

From wind-tunnel studies of artificial barriers situated at various points on undulating ground, it appears that a barrier is most effective when it stands at the top of a hill or on the windward slope and much less effective when it stands on the leeward slope or in the valley between two hills which follow one another in the direction of the wind (Blenk 1952).

Effect of a Series of Parallel Shelterbelts on the Wind Velocity

Conflicting opinions have been expressed concerning the influence on wind velocity of systems of shelterbelts or screens normal to the wind direction. Investigations of a series of green willow windbreaks, 330 ft apart and 30-45 ft high, showed that their effect on wind velocity was not cumulative (Purdue Univ. 1940). Bates (1945) found that, where 4 parallel barriers, normal to the wind direction, were separated by distances of 25, 20 and 30 times their common height respectively, the effect on wind speed was the same as that of 4 barriers of equal length, height and type acting independently; no cumulative effect was exhibited. However, their most important effect is to create a "larger coherent mass of stilled air" with a zone "7-12h stretching laterally from the ends, giving some small degree of protection". From studies both in the field and in the laboratory Nøkkentved (1940) has concluded that, at the usual distances apart (10-15h), parallel shelterbelts show no cumulative influence but some such effect might be obtained if the belts were planted sufficiently closely together. These investigations have been developed by Jensen (1954) who found, with model windbreaks, that when the screens were spaced more than 5h apart, there was only a slight difference in

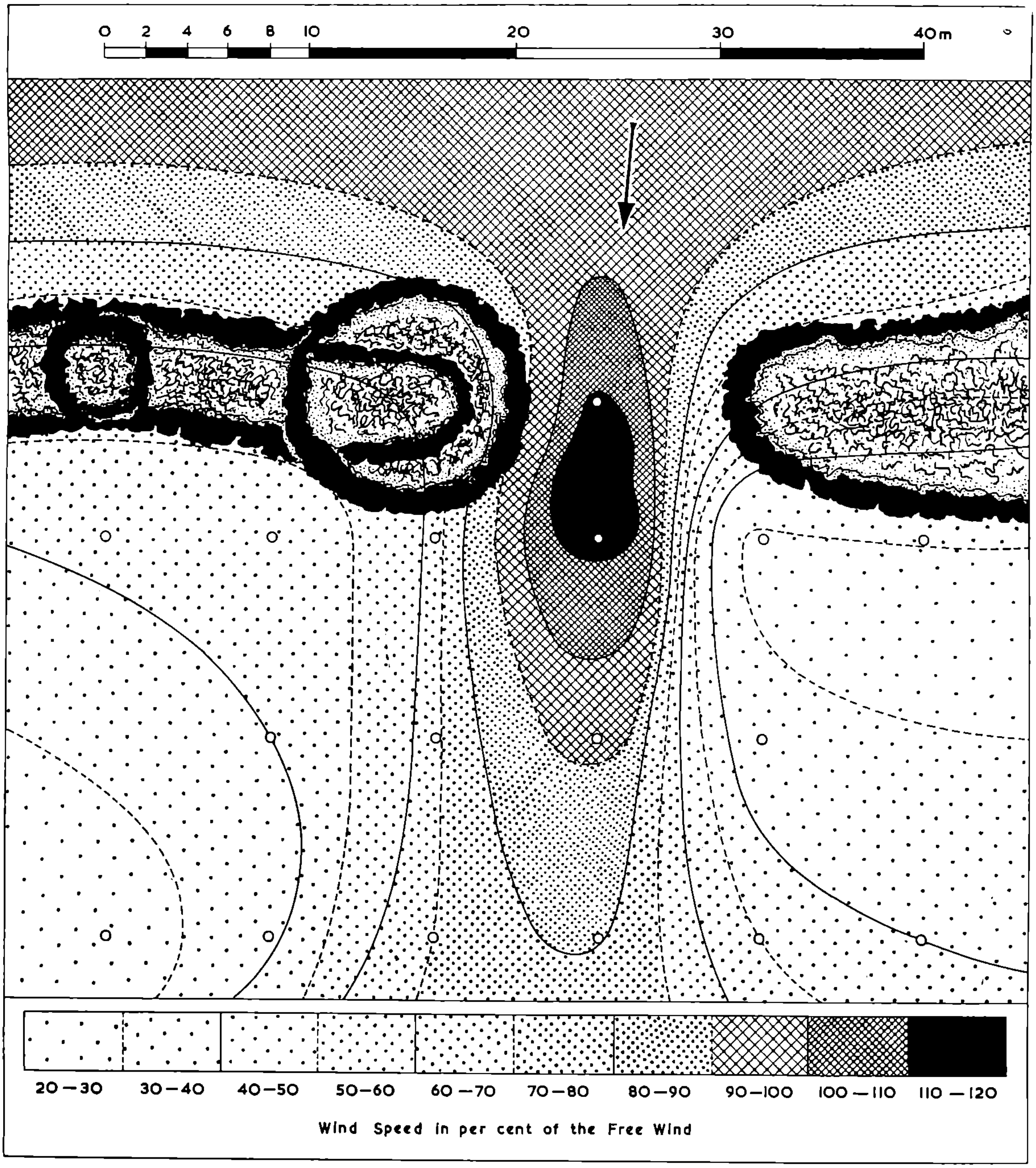


FIGURE 14. Wind conditions in the vicinity of a gap in a shelterbelt, (after Nägeli).

the shelter effect of the two screens and little deviation from the effect of a single screen. With a spacing between screens of 2h, the shelter effect was considerably greater close to the screen and out to a distance of about 20h, from which point the shelter effect was less than that of a single screen or of the systems of screens with greater distances between barriers. Measurements of parallel hedgerows in nature showed no significant cumulative effect on the wind velocity.

However, in investigating wind velocities between two belts, Nägeli (1946) observed that at no point between them was the free wind speed attained and concluded that belts could be so laid out that their zones of velocity reduction overlapped, although this might be possible in very rare cases only. It has been stated that provided two shelterbelts are not more than 30 times their common height apart, the full unobstructed wind will not be regained in the zone between the belts and that, if the distance between the belts is 20 heights, the wind reduction for the intervening area will be appreciable (Edlin 1953). Whilst this might appear to be probable theoretically, there is as yet no scientific evidence in confirmation.

Effect of a Wooded Landscape on the Wind Velocity

It has been observed that, as the wind passes over an extensive land mass, a reduction of velocity occurs; a region with shelterbelts and hedges offers more resistance to the wind than an area which is relatively treeless (Braak 1929). To obtain information on the effects of open and densely wooded landscapes on the velocities of the wind in the layers near the ground, measurements have been made during the passage of a westerly wind across Jutland (Jensen 1954). Two measurement lines were selected, the first passing through South Jutland, sparsely provided with hedgerows and woodlands, and the second through Mid-Jutland which contains a very large number of shelterbelts and plantations. The lines were surveyed in detail and "roughness coefficients" allocated according to values obtained in preliminary wind-tunnel studies on multiple screens. Values of wind speed recorded on the first line (roughness coefficient 0.003) showed that within a distance of about 10 km the velocities near the ground were reduced by 20 per cent; on the eastern part of this same line (roughness coefficient 0.020) the velocity was only 55 per cent of its original value until, passing over a 10 km stretch of sea, it again rose to 75 per cent. On the second line (roughness coefficient 0.010-0.015) the velocity was reduced by 50 per cent within a distance of 20-30 km.

Regarding the relation between the velocity of the geostrophic wind and that at 2 m above ground, on sites with different roughness coefficients, variations of great magnitude in the wind speed were observed by Jensen to be transmitted to the wind at 2 m above ground at the rate of 75-90 per cent of the geostrophic wind velocity. At the coast of Jutland the ratio between the wind velocity at 2 m and the geostrophic wind was found to be 0.38; in open terrain, with roughness coefficient 0.003, 0.29; in hilly and densely wooded terrain, with roughness coefficient 0.010-0.015, 0.21.

Section 2. Temperature

Basis of Heat Exchange

By day, the earth's source of heat, the sun, transmits heat by radiation, of which a considerable proportion is reflected by the surface of the clouds or scattered diffusely into universal space and is ineffective concerning the heat economy of air and ground. At the ground surface, a further loss is incurred by reflection, long-wave radiation, evaporation, convection and conduction, the remainder being supplied to the ground. During the night, when incoming radiation is cut off, the land surface loses heat through outgoing radiation and evaporation and the colder, and therefore heavier, air layers form beneath the warmer, lighter ones. In this way, the temperature profile shows increase in temperature with height above ground, a condition known as temperature inversion, in contrast to conditions at mid-day. In the course of the day, air movement caused by wind and convection hinders stratification but, at night, a stable vertical stratification occurs, the stability increasing as further cooling proceeds. Consequently, night is the time of least wind velocity at the ground surface.

The rate of heat exchange at the ground surface is conditioned by the nature of the surface. Bare ground absorbs heat readily and loses it quickly during outgoing radiation conditions. Vegetation increases the surface of absorption; the rise in temperature is reduced and similarly the rate of loss during the night. Plants therefore modify temperature fluctuations near the ground. High forest has the effect of raising the "ground climate" or the surface of absorption some distance above the ground, i.e. to the crown space, where radiation is absorbed and emitted, the free wind is retarded and water is given off to the air as it is in the open. A separate climate arises in the trunk space, which is peculiar to forest conditions. The trunk space normally has a more equable climate than the tree crowns since the vigorous heat exchange taking place at the crown surface during the day is transmitted only gradually to the trunk space and during the night the cold air settles above the crowns unless the stand is very thin and the cold air can sink to the forest floor.

Temperature Conditions on Forest Margins

Temperature relationships near the ground, the changing conditions of heat exchange, the influence of topography and forests on air temperatures and the climate of stand borders and clearings, described in detail by Geiger (1950), are concerned in the effects of shelterbelts on the temperatures of sheltered areas. To some extent, the conditions which obtain on forest margins are applicable to shelterbelts also, particularly in the case of wide belts.

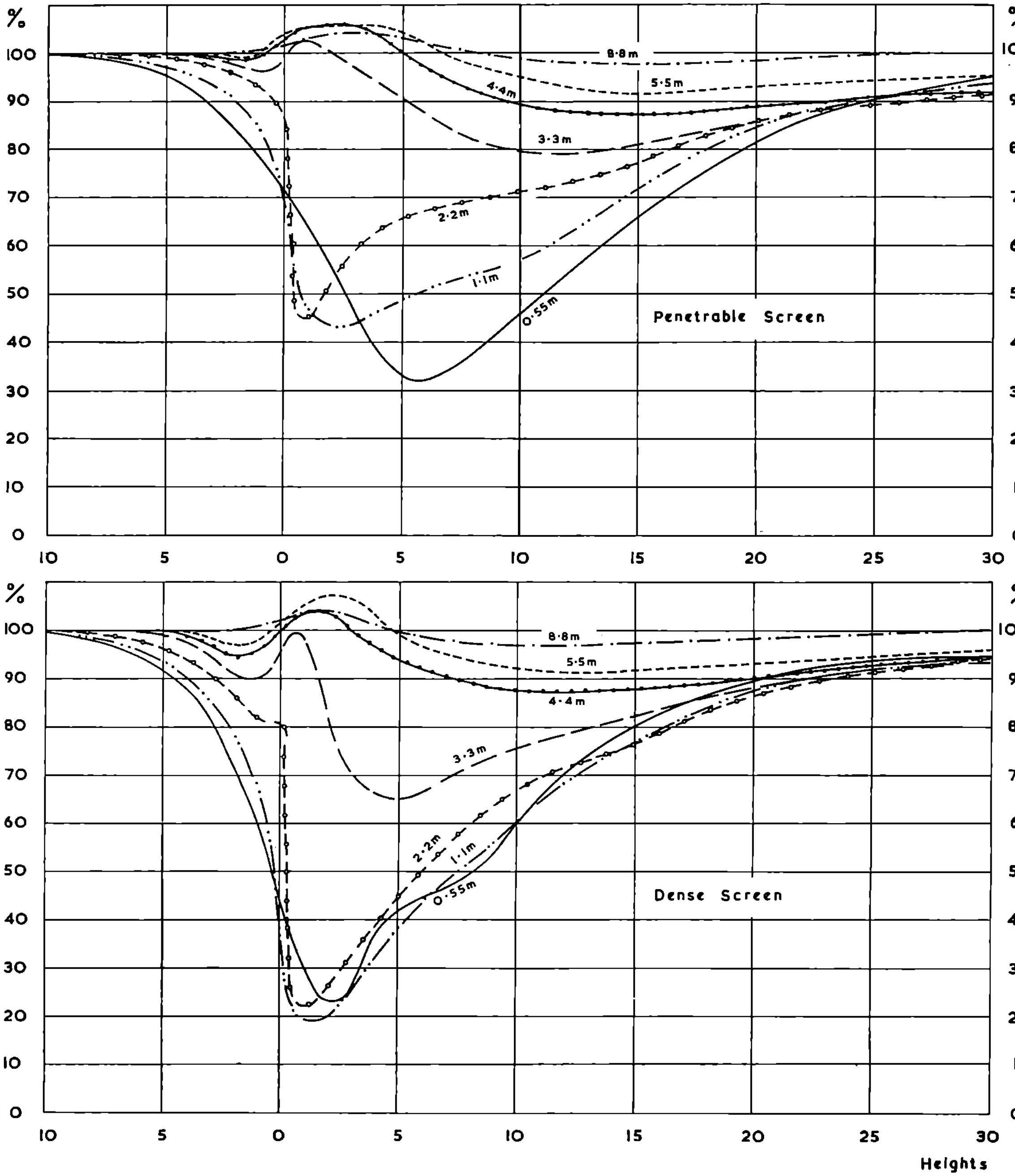


FIGURE 15. Relative wind velocities at different heights above ground in the vicinity of penetrable and dense windbreaks, 2.2m in height. (m = height in metres) (after Nägeli).

Forests are surrounded by a belt of increased temperature fluctuations, chiefly as a result of the heightened effect of radiation by reason of the greater calmness of air (La Cour 1872). Stagnation of the air on the stand margin allows a stable stratification of cold air which is constantly sinking from the crown space. The morning heating has to overcome the stability of the nocturnal temperature stratification; the evening cooling is furthered by its establishment.

On the other hand, frost protection at night on the edge of a wood is brought about not only indirectly, by reason of the warmer trunk space air, but also directly through the restricted net outgoing radiation caused by the tree crowns. Also, during the day, when the air layers near the ground become heated over open country but remain cool in the forest under the screen of the canopy, the cooler air of the trunk space may flow out into the open as a diurnal forest wind (Geiger 1950).

The climate at the stand border results from two fundamentally different causes. Firstly, it is a transition climate between that of the trunk space and that of the open country and the contrast leads to an exchange of their properties. Secondly, the edge of the stand is like a high step in the land and, according to the direction it faces, it catches insolation or withholds it from the open region (Geiger 1936).

Air Temperature Conditions in the Vicinity of Shelterbelts

The average summer temperatures between shelterbelts are somewhat lower and the average winter temperatures somewhat higher than in the open steppe but these differences are slight (Nägeli 1941). To any appreciable extent (more than 1°C), the direct effect on the temperature of the air layers near the ground is felt only at a short distance from the shelterbelt—3 times the height of the belt (Gorshenin 1941). Windbreaks increase the average temperature of the air (Flensborg 1926), an opinion probably based on the observations of La Cour (1872) to the effect that protection against wind causes higher temperatures in the daytime but lower temperatures at night; the average increase in temperature in the sheltered zone was recorded as $1\frac{1}{2}$°C. It was assumed that this greater daily amplitude caused a greater danger of night frost, a fact which has been pointed out by Bodrov (1936).

Bates (1911) has mentioned the increased diurnal amplitude in sheltered areas and reported that, on sunny days in America, with light to moderate winds, maximum temperatures at 4 ft above ground in the zone between 2h and 5h behind a dense barrier exceeded those in the open by 2-5°F and minima were about the same amount less at night, little difference being found beyond about 10h. Under British conditions of intermittent sunshine, the differences obtained are less and of course rarely occur day after day (Gloyne 1954). More recent figures from Holland indicate maximum differences up to 5-6°F about 4 in. above the surface but 1-3°F at 4 ft within a zone about 10h wide (van der Linde and Woudenberg 1951).

Bates has also recorded that the highest diurnal maximum and the lowest minimum are to be found in those places where the wind is reduced most. Clouds, by preventing insolation and outgoing radiation, reduce the effect of a windbreak on air temperature. During precipitation the effect of a windbreak is beneficial since it checks the wind velocity, thereby preventing excessive cooling of the air through rapid evaporation from the wet surface. The daily superheating of the air amounts to approximately the same value whether the temperature outside the sheltered zone be high or low but, relative to the total amount of heat available for plant growth, it is most important in the spring and autumn when the supply is lowest.

The daily progress of temperature is dependent on the weather; the clearer and drier the weather the greater the daily amplitude. During the first half of the day, when the balance of warmth is positive, i.e. when incoming radiation surpasses outgoing radiation, the shelterbelt produces a warming effect. In the second half of the day, from about 1500 hr to sunrise next morning, when the balance is negative, the belt produces a cooling effect. During very hot days the temperature in the zone adjacent to the belt may rise 6-7°C; this may have an unfavourable effect upon plant growth and, in conditions of extremely high temperatures, may cause "sun scald" or scorching (Bodrov 1936). This excessive insolation is furthered by reflection from the trees of the shelterbelt (van der Linde and Woudenberg 1951) and is exhibited particularly on a still day (Geiger 1950). When incoming radiation is intermittent, as a result of variability in the cloud deck, the temperature is higher practically all day long in the sheltered area than in the open.

On the other hand, shading from incoming solar radiation occurs on the opposite side of the shelterbelt thus causing lower air temperatures. The width of the shaded or insolated zone depends on the time and the orientation of the shelterbelt (Geiger 1950). A method has been devised to determine graphically the width of shadow beside objects with horizontal upper edges for each hour of the day and each day of the year (van der Linde and Woudenberg 1946).

A higher wind velocity produces increased dynamic convection between the air layers near the ground and, consequently, decreased temperature gradients. This means lower temperatures at the ground by day and higher at night. On a still night, with little or no wind, there is a greater danger of night frost. Because of the effect of shelterbelts in reducing wind velocity, the danger of night frost in enclosed sheltered areas is considerably higher than in unsheltered regions (Geiger 1950). However, frosts related to the movement of cold air masses will be reduced by shelterbelts and the possibility of their occurrence in sheltered areas will be less (Bodrov 1936). Also, the theory of stagnant air is applicable only as long as there is wind; on calm nights the danger of night frost should not be greater, apart from other influences, in a sheltered area (van der Linde and Woudenberg 1951). On such nights, however, radiation from the branches and leaves of the trees in the shelterbelt will cause a slowly descending current of cold air next to dense belts and this will prevent a uniform danger of frost in all parts of the sheltered area. Gorshenin (1941) confirms that frost danger is greatest with dense shelterbelts which allow stagnation of the air on their margins.

It is apparent that the influences of shelterbelts on local temperatures are dependent on microclimatic conditions and few general conclusions can be drawn regarding their quantitative effect on the temperature range. These influences may be summarised as follows:

- (i) Reduction of wind velocity, causing a sheltered area to leeward and, to a smaller extent, to windward of a shelterbelt, brings about a reduction of thermodynamic exchange between the air layers, which results in generally higher temperatures. However, when disturbance is reduced to a critical value, thermal stratification and stagnation of the air occur within the sheltered zone, with greater danger of night frost.
- (ii) Shading causes lower temperatures on the side of the shelterbelt away from the sun; on the opposite side insolation produces higher temperatures.
- (iii) Higher daily temperatures and lower night temperatures give rise to a greater diurnal amplitude within the sheltered area.
- (iv) Restriction of outgoing radiation from a a narrow strip along the shelterbelt margin by the tree crowns, which will depend on the species and crown form to a certain degree, together with the warmer air flowing out from the trunk space, should theoretically produce higher night temperatures on the shelterbelt margin. This may be counteracted by the downward flow of cold air from the crowns.

The unfavourable effects which shelterbelts exert on the temperature regime are connected chiefly with night frost. This danger can be minimised by ensuring that shelterbelts are partially penetrable to the wind but not sufficiently open as to cause cold draughts through the trees. Siting and construction will play an important part in the temperature relationships, which, generally speaking, are more favourable for plant and animal welfare.

Effect of Shelterbelts on Soil Temperatures

Shelterbelts have a positive influence on the soil temperatures in their vicinity (Kreutz 1938). Bates (1911) studied the effect of windbreaks on soil temperatures at a depth of 50 cm and found a temperature under the trees $3\frac{1}{2}$°C below that in the open. Further, he discovered that the degree of influence at this particular depth varied according to the season; during increasing declination of the sun, i.e. in Spring, the value of the influence was greater; during decreasing declination, i.e. in Autumn, it was lower. This phenomenon must be closely related to that regarding the diurnal course of air temperatures throughout the year, mentioned by Bodrov (1936). The differences observed were generally less than 1°C however.

Anderson (1943) records the following soil temperatures at various distances to the west of a leaf-tree belt, 2.5 m high, during June/July 1915:

Wind	Temps. at most westerly station		Temp. differences from those of the most westerly station (degrees C increase)					
			W. of belt: 55 m		$37\frac{1}{2}$ m		$12\frac{1}{2}$ m	
	depth 5 cm	10 cm	depth 5 cm	10 cm	depth 5 cm	10 cm	depth 5 cm	10 cm
Westerly	16.33	15.53	0.0	0.0	0.08	0.04	0.12	0.21
Easterly	16.31	15.47	0.0	0.0	0.03	0.05	0.60	0.58

The lower strata of the soil are heated by the conduction of warmth from above. Conduction is increased by a moderate amount of moisture in the soil, yet evaporation of moisture may reduce the surface temperature and thus reduce also the amount of heat to be conducted downward (Bates 1911).

Section 3. Atmospheric Humidity

Measures of Atmospheric Moisture

Of the measures of the moisture content of the air near the ground, the expression "relative humidity", the percentage degree of saturation or the ratio between the actual vapour pressure and saturation vapour pressure, has been commonly used but is probably the least satisfactory from the aspect of shelterbelt and forest influences. A constant relative humidity represents neither a constant vapour pressure in the atmosphere nor a constant evaporative power. Relative humidity varies inversely with temperature in such a way that, with a 1°F rise or fall in temperature, there is a change of 1-5 per cent in relative humidity in the opposite direction.

"Saturation deficit", the difference between the actual and saturation pressures, should be the most useful climatic measure to indicate evaporation from water, soil or foliage and transpiraton by the plant (Kittredge 1948). The term means more than relative humidity ecologically (Braun-Blanquet 1932), and may vary greatly even when the relative humidity remains constant for it rises with temperature at an accelerating rate.

The hygrometric state of the air may also be expressed by means of the "vapour density" or "absolute humidity", the density of the water vapour present in the air, and the "dew point", the temperature for which the actual and saturation vapour pressures are the same.

Humidity Relationships in a Forest Stand

Before sunrise there is high humidity in all layers from the forest floor to above the crowns of the trees. After sunrise the crown surface begins to dry out and during the morning there is a sharp decrease in relative humidity in and above the crowns whilst on the forest floor nocturnal moisture conditions are still evident. Later, as the sun gets higher and the wind freshens normally, their influences penetrate the interior of the stand and the divergence between the relative humidity in and above the crown space and that at the forest floor is decreased; this is the time of the mid-day minimum. In the evening type of humidity distribution the greatest humidity differences at the various heights are to be observed, since the air above the crowns is still under the dominance of the daytime drying hours but the steady transfer of water vapour from the ground begins to be more effective as the temperature within the forest gradually decreases (Geiger 1950).

As a result of the temperature differences in the lower-most air layers, movement of air from a plantation into the surrounding area occurs. This very light wind, known as the diurnal forest wind, may be recognised by its ability to convey cool humid air from the trunk space into the open (Herr 1936, Dörffel 1935). In this way the moisture relationships within a forest stand will affect the humidity of the adjacent area, though probably restricted to a narrow strip along the forest margin.

Humidity Relationships in Sheltered Areas

Numerous investigations have shown that the humidity, both absolute and relative, of the climate near the ground between shelterbelts is usually higher than in the open and this excess has been expressed as 2-3 per cent of relative humidity and 0.5-1 mm of absolute humidity (Gorshenin 1941). Summarising earlier work, Nägeli (1942) suggested that the influence of shelterbelts on relative humidity is small in so far as the average value is regarded but the humidity in sheltered areas is constantly higher than in the open, whilst minimum values in the open are considerably lower than between shelterbelts. Later, he found that in the daytime there is a distinctly perceptible increase in the average relative humidity in sheltered regions (Nägeli 1943). Kreutz (1938) observed a similarly distinct increase in relative humidity within plots screened by artificial windbreaks; since the screens were not of living material there was no question of water vapour being conveyed from the screen and therefore the increase was ascribed to the fact that the water evaporated from the soil and growing crops is retained longer in a sheltered area owing to the reduced air movement.

Bates (1911) records the following figures for saturation deficit at different distances to leeward of a windbreak:

Distance (multiples of height)	Saturation Deficit (inches Hg)	Temperature (°F)
1	0.743	85.1
5	0.788	86.7
10	0.776	86.9
In the open	0.697	84.9

Kittredge (1948) has suggested that the differences in saturation deficit reflect the differences in the corresponding temperatures rather than in moisture content of the air.

Measurements of relative humidity made between 1913 and 1915 (Esbjerg 1917, Andersen 1943) at 50 cm above ground and at various distances from a leaf-tree belt about 3 m high, with winds between force 2 and 3 on the Beaufort scale, were as follows:

Measurement Point	Wind Direction	Relative Humidity (%)
30 m West of belt	W	77
6 m ,, ,, ,,	W	76
6 m East of belt	W	80
30 m ,, ,, ,,	W	77
30 m ,, ,, ,,	E	65
6 m ,, ,, ,,	E	66
6 m ,, ,, ,,	E	72
30 m ,, ,, ,,	E	67

More detailed observations of the effect of shelterbelts on relative humidity (Kas'Yanov 1950) are summarised in the following table:

Point of measurement	Relative Humidity (%)				
		Apr.	May	Jun.	Jul.
	1946				
In the shelterbelt system		66.4	55.6	42.6	54.1
In the open steppe		63.7	51.6	38.6	51.6
	1947				
In the shelterbelt system		68.6	65.0	51.0	47.0
In the open steppe		65.3	63.0	49.0	44.0
	1948				
In the shelterbelt system		63.0	53.0	41.5	50.0
In the open steppe		60.0	49.6	39.3	47.2

Generally speaking, the absolute air humidity may be assumed to be higher in a sheltered region than in the open; when the temperature in a sheltered area is temporarily higher, the relative humidity may be lower than in the open however, in spite of the higher absolute humidity (van der Linde and Woudenberg 1951). Under conditions when the vapour pressure near the surface is 7-12 mm of mercury one may expect to find increases of up to about 2 mm during the day within a 10h wide strip adjoining a shelterbelt. At night there is an associated fall of dew (Kreutz 1952b).

Changes in atmospheric moisture due to shelterbelts occur in full dependence with the daily weather progress (Bodrov 1936). "The most marked positive influence of shelterbelts appears to be during the second half of the day when the warmth balance on the surface of vegetation is negative. During the hours of sunset (when the weather is dry and hot), the deficit in moisture may drop under the effect of belts at an average of 15 per cent over a distance of 1 km, whilst the fall at points near the belt may reach 50-60 per cent. During the morning hours, when the balance of warmth is positive, the influence of shelterbelts becomes opposite, as at that time they produce a drying effect on the air. As a result of this the moisture becomes less and the moisture deficit soon after sunrise may rise on the average by 20 per cent over 1 km distance between belts. At mid-day, with a somewhat even balance of warmth, the shelterbelts begin to produce favourable effects. In dry and hot weather they increase the atmospheric moisture to a distance of 500-600 m. Furthermore, under the influence of vertical mixing of air masses, the moisture falls below that of the air in the open steppe but remaining, on the average, equal to it."

The humidity of the air is influenced by wind, air temperature, transpiration and evaporation from vegetation and the shelterbelt itself and by the moisture content of the surface soil. It also depends on the time of day and season and on weather conditions. No general quantitative values can be assumed for the increased degree of humidity in the vicinity of shelterbelts because of the extremely varied conditions under which measurements have been recorded. However, it would appear that the moisture content of the air in sheltered regions is significantly higher than in regions where the wind is unobstructed.

Section 4. Evaporation and Transpiration

Relation of Evaporation to Other Climatic Factors

Evaporation, the loss of water from a damp object or a free water surface to the atmosphere, has been considered to supply the best index of efficiency of a shelterbelt (Bodrov 1936). In areas of low rainfall it is evident that evaporation must play an important role since it controls the degree of dryness of a climate.

Evaporation is dependent upon the combined effect of humidity, wind, temperature, atmospheric pressure and radiant energy. Without air movement, evaporation is closely related to the vapour-tension deficit. Temperature exceeds wind velocity in its influence on the rate of evaporation (Shull 1919). However, it has been observed by several investigators that, when temperature and relative humidity in an area are fairly uniform, the differences in evaporation values are controlled almost exclusively by wind and the distribution of evaporation closely follows that of wind velocity.

Investigations to evaluate by analysis the importance of the vapour pressure deficit and wind as factors of the evaporation rate (Kucera 1954) have determined a multiple regression for the rate of evaporation as a function of the vapour pressure deficit and wind velocity. The correlation of evaporation to the saturation deficit exceeded 70 per cent; wind, as a separate factor, showed only limited correlation but, as a component factor, it decreased variance in evaporation unrelated to saturation deficit by 54 per cent. Increasing wind speed increased the rate of evaporation when the degree of humidity remained constant and wind effectiveness was most pronounced in the initial velocity classes and diminished as air movement increased. Under conditions approaching condensation, as on still nights when temperatures of evaporating surfaces dropped considerably below those of the air, the vapour pressure deficit was an unreliable index of the evaporation potential.

Observations recorded by Maran and Lhota (1952) indicate that on calm days the evaporation curve roughly follows the curve of temperature; a cloudy sky and a wind of varying velocity cause irregular changes in the rate of evaporation and, at lower temperatures, wind becomes the governing factor. The evaporation amplitude reaches a peak with a cloudless sky.

Reduced evaporation from the ground surface and from plants involves a reduction in heat consumption for evaporation and thereby a higher soil and air temperature; this fact is of quantitative importance (Jensen 1954).

Relation of Transpiration to Other Climatic Factors

Transpiration, the physiological release of water by the actual plant, is of great importance to vegetative growth. The existence of a direct relationship between transpiration and the relative humidity of the air has been established experimentally by Darwin (1914). The rate of loss of water by the plant obeys Dalton's law of evaporation within a certain very narrow range of relative humidity; with an increase of relative humidity (this means a lower temperature if the magnitude of deficit is maintained) the rate increases; with a decrease of relative humidity (accompanied by a rise in temperature) the rate diminishes (Maximov 1929). Thus, quite apart from possible stomatal movements, the influence of atmospheric humidity on transpiration is very complicated and cannot be expressed by a simple formula.

Briggs and Shantz (1916) calculated the correlation co-efficients between transpiration and the various environmental factors: the vertical component of radiation, air temperature and wet-bulb depression. Transpiration showed the greatest dependence on the intensity of radiation, thus accounting for the great divergence between day and night transpiration rates. Transpiration and evaporation curves are frequently found to parallel one another (Braun-Blanquet 1932).

Wind can accelerate transpiration considerably by the removal of humid air from the leaf surface, thereby promoting diffusion through the stomata, and by causing bending movements of the leaf lamina, bringing alternate contraction and expansion of the intercellular spaces and facilitating the exit of saturated air and the entrance of dry air (Symkiewietz 1924). It is frequently mentioned that transpiration increases under the influence of wind up to a velocity of 2-4 m/sec, after which the rate of transpiration is not affected by an increase in the wind velocity. However, most of the investigations which gave rise to this conclusion were conducted with individual plants or parts of a plant and not with actual growing crops. Using boxes containing growing material of clover and grass in a wind-tunnel, Jensen (1954) has established that the loss of water from plants in natural conditions increases in proportion to increases in velocity and this he ascribed to the bending influence of the wind and the greater the penetration the higher the velocity, thus exposing a larger stomatal surface to the air current. In calm conditions transpiration is proportional to the saturation deficit and the same ratio was found to obtain in the wind to some extent. He observes further that the physical law that evaporation increases with wind velocity may be said to apply also to transpiration up to velocities of 10 m/sec; above this, transpiration increases at a lower rate than that indicated by the evaporation law.

It has been observed that, with the same wind velocity, an immobile attached leaf transpired less water than a leaf free to bend and move with the wind. On the other hand, mechanical deformation, as well as increased loss of water under the influence of wind, may lead to closing of the stomata and, consequently, to a retardation of the gaseous interchange between the intercellular spaces of the leaf and the surrounding atmosphere. These considerations complicate the problem of the effect of wind on transpiration and render quantitative relation between wind velocity and transpiration rate more difficult (Maximov 1929).

Effect of Shelterbelts on Evaporation

Since evaporation depends upon various climatic factors, which are controlled in some measure by shelterbelts, it follows that shelterbelts also influence the rate of evaporation in their vicinity. This influence was shown by La Cour (1872), who found a distinct decrease in evaporation rates both to windward and to leeward of tree belts. His results are not considered altogether reliable, however, in the light of more modern research methods.

The evaporative or desiccating power of the wind has a marked effect on the growth, and frequently the existence, of vegetation. The loss of moisture by evaporation is the crucial feature of the effects of the wind on crops. The distance from a windbreak to the area of greatest protection from desiccation depends upon the position of the mass of foliage which affords the protection. With a dense grove, it is immediately in the lee of the trees; with a narrow belt of trees which lacks lower branches, it may be as far from the trees as 5 shelterbelt-heights and it moves outwards as the velocity of the wind increases. The influence on evaporation is not of great importance beyond 10h (Bates 1911).

Conflicting opinions as to the extent of shelterbelt influences on the rate of evaporation have been recorded. Nägeli (1943) has stated that the variations in evaporation within the zone of shelterbelt influence are closely correlated with the wind abatement, more or less confirming an earlier conclusion by Woelfle (1938) that evaporation is almost proportional to the square root of the wind velocity when all other conditions are the same, but that the evaporation rate is markedly decreased near the belt although to a lesser degree than the speed of the wind. The minimum wind velocity was found slightly to leeward of the shelterbelt but the evaporation minimum always occurred within the belt. This observation does not conform with the results obtained by Bates (1911) and shown in Fig. 16.

Shelterbelt influence has been held to extend to a leeward distance exceeding 60h with wind velocities of 2.5-3 m/sec and up to 100h with winds of 5-6 m/sec (Bodrov 1936). Within a 1-km plot in the open and surrounded by shelterbelts 17 m high, the saving in moisture due to decreased evaporation amounted to 17 per cent of the total with winds of 2.5-3 m/sec and 25 per cent with winds of 5-6 m/sec. However, this observed protected area is wider than that generally found. Relative figures for evaporation measured at 50 cm above ground (Esbjerg 1917) and at various distances from a leaf-tree belt 2.5 m high showed a zone of effect extending 20h windward and 24h leeward; at 22h to windward 24 mm more water was evaporated from a free water surface than at 5h, representing 60 per cent of the total precipitation during May in the particular region of Denmark where the experiments were conducted. Average figures for 4 shelterbelts in Japan have shown that at leeward distances of 1h, 5h and 10h from the belt the corresponding evaporation rates were 40, 60 and 80 per cent of the open ground evaporation; evaporation was much lower in the belt than to windward, decreasing from the windward to leeward side of the

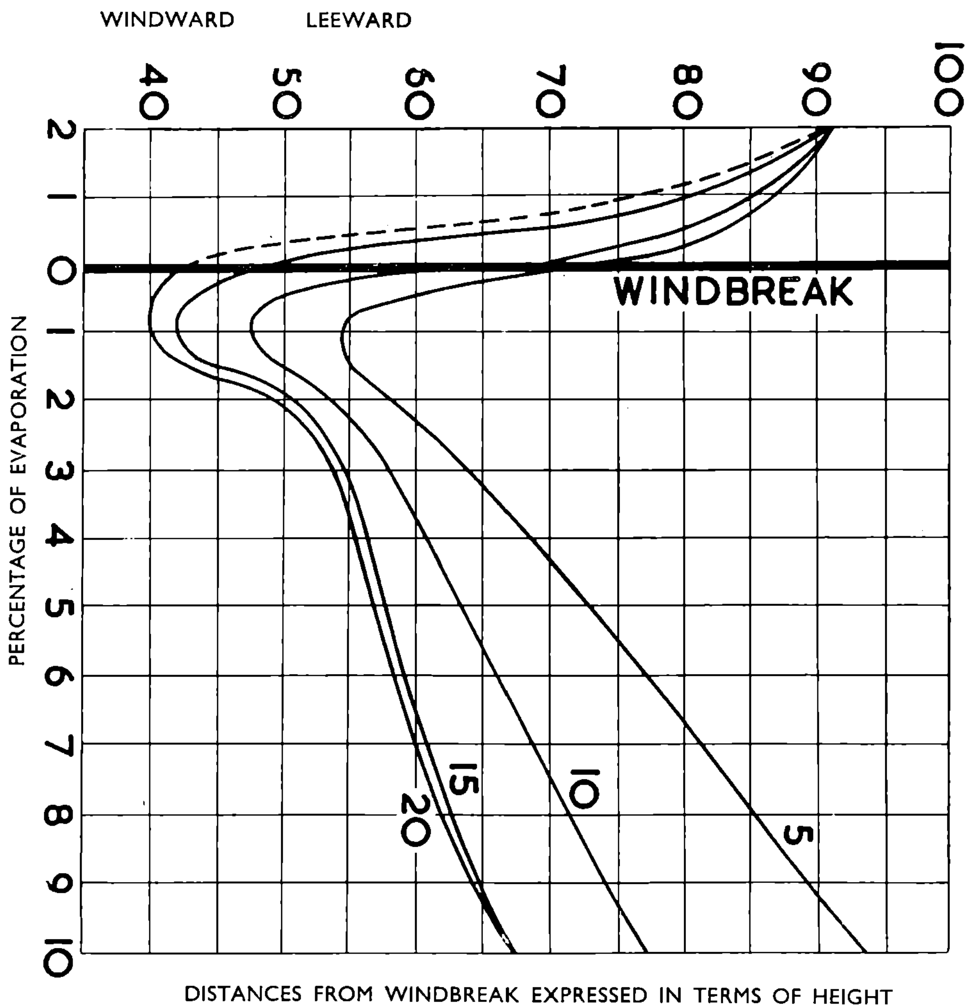


FIGURE 16. Relative evaporation rates in the vicinity of underplanted cottonwood (Poplar, *Populus* species) groves in the United States of America for various wind velocities of 5, 10, 15 and 20 mi/hr. Average height 75 ft.; 70 readings, (after Bates).

belt, and was very little more in the open, closely to leeward, than within the belt itself (Iizuka *et al.* 1950).

It is apparent that there is a significant reduction of evaporation within sheltered areas. Values recorded for this reduction are, on the average, 20-30 per cent (Warren 1941, Kas'Yanov 1950). This reduction is important in relation to conservation of moisture and crop yields (Gorshenin 1941) although it may be a disadvantage during harvesting of cereal crops (van der Linde and Woudenberg 1951). Its value applies particularly in low rainfall areas and regions where the majority of the annual precipitation occurs when there is no vegetative covering on the soil (Hennebo and Illner 1953). Dense shelterbelts may be considered to be less favourable in reducing evaporation than moderately penetrable belts since the intense turbulent mixing to leeward of dense barriers transports water vapour rapidly from the sheltered area, thus promoting further evaporation (Bodrov 1935).

Effect of Shelterbelts on Transpiration

Few research workers have examined the effects of shelterbelts on transpiration under natural conditions owing to the difficulties of experimental study of this process. However, there is sufficient evidence to show that any reduction of wind velocity will check the rate of transpiration to some extent. Consequently, the abatement of wind velocity within the vicinity of a shelterbelt must cause a marked reduction of transpiration within the sheltered area.

Wilting of vegetation and deformation is produced by increased loss of water from the plant under the influence of wind. This leads to closing of the stomata which retards carbon assimilation; respiration continues in spite of the closed stomata and the plant soon starves (Maximov 1929). Also, independent of the closing of the stomata, a deficiency of water retards assimilation (Bernbeck 1924), even though wind may cause mass movement of air through the intercellular spaces of the plant, which could be regarded as facilitating rather than impeding the access of carbon dioxide to the assimilating cells. Shelter should therefore be more favourable for carbon assimilation and plant growth.

Field studies of the water relationships of shelterbelt trees in Japan have shown that evaporation and transpiration are higher to windward except when the leeward side of the belt was exposed directly to solar radiation; the water content of the leaves was always found to be lower on the windward margin than on the leeward edge and it was concluded that wind reduces the water content of leaves but the effect of this on transpiration was less clear (Satoo 1952).

Section 5. Soil Moisture, Precipitation and Snow Distribution

Soil Moisture Relationships in Sheltered Areas

Soil moisture relationships in areas protected by shelterbelts are a complex combination of the effects of tree belts on the various climatic factors: precipitation, whether in the form of rainfall or as melting snow, fog or dew, as well as evaporation, transpiration, atmospheric humidity, air and soil temperatures and solar radiation. The trees within the shelterbelts, particularly on the margins, also affect the soil moisture content directly, the distance to which this influence extends depending on the spread of the root systems of the trees.

Whilst shelterbelts are not considered to influence the total annual precipitation of an area, they exert a considerable influence on the local distribution of rain and snow. In fairly exposed areas, rain is usually accompanied by wind. Shelterbelts intercept rain under such conditions so that a higher precipitation occurs over a belt than over a similar surface area in the open. A "rain-shadow" zone develops on the leeward side of the shelterbelt since little or no rain falls on this area. The distribution depends on the velocity of the wind (Kreutz 1952a); in the case of weak winds the distribution of rainfall near a belt remains fairly uniform but with higher velocities and the increased carrying power of the wind there is an appreciable alteration. This distribution is clearly dependent on the structure of the shelterbelt; the denser and higher this is, the more pronounced will be the leeward "rain-shadow" zone. Lammert (1947) has recorded a "rain-shadow" zone, 30 m in width, to leeward of a dense poplar plantation 40 m in height and 20 m wide.

Results of investigations of the interception of sea-fog particles by an experimental shelterbelt, 2 m high and 13 m wide, established on grassland in a coastal fog-belt in Japan, showed that amounts of 1mm/hr were intercepted on the windward side of the belt with a fog moisture content of 0.3 g/m^{-3} and wind velocity of 3.4 m/sec in the open (Kashiyama 1953).

Dewfall in areas sheltered against wind has been found to be 200 per cent greater than on exposed ground; the difference was less in weather favourable for dewfall than on windy nights. The heaviest dewfall was found over a distance of 2-3h on the leeward side of the hedge or windbreak (Steubing 1952). The agricultural significance of increased dewfall brought about by shelterbelts will depend not only on the total quantity of the increase but also on the normal rainfall and its annual distribution (Hennebo and Illner 1953). Walter (1952) doubts whether the differences in dewfall should be considered as of ecological significance since the corresponding amounts of water are small. Although dew can be absorbed through plant leaves and, by this means, a certain enhancement of the soil moisture content is possible, it has not been clearly established.

Extensive research has been conducted on lodgement of snow near shelterbelts and its influence on soil moisture; in regions where a large proportion of the total annual precipitation occurs during the winter months in the form of snow, this aspect of shelterbelt effects is particularly important. Results of this research are discussed in a following section.

Laboratory and field tests have confirmed the increased moisture content of the soil in sheltered areas (Gorshenin 1941). In a strip between 10h and 12h distance from a shelterbelt the soil moisture content during the whole growing season of vines has been observed to be 25-30 per cent higher, to a depth of 1 m, than in the unprotected area (Masinskaja 1950). The protective effect in this case fell to zero at 20h to leeward, whilst in the immediate neighbourhood of the belt the soil moisture was 20 per cent less than in the unprotected area.

Kreutz (1952b) records that the soil moisture content of bare ground in April was 6.5 per cent where exposed to wind and 12.1 per cent between shelterbelts; measurements under a growing crop between May and September showed an average moisture content of 6.375 per cent in exposed places and 10.475 per cent between the belts.

The several factors controlling soil moisture conditions cannot be isolated easily. In an area adjoining a shelterbelt, there will be, on the one hand, increases due to snow accumulation, reduced evaporation and drip from the trees. On the other hand, there will be decreases due to "rain shadow" on the leeward side of the shelterbelt and root spread, the latter drawing off moisture from part of the sheltered area. Also, the leaf fall from the trees will affect the organic content and absorptive power of the soil in the neighbourhood of the belt. A study of the available literature reveals that the moisture content in sheltered regions is generally appreciably higher than in the open but the consequent delay in drying-out of the soil in the spring and summer may not be advantageous at all times for agricultural operations, particularly close to a shelterbelt.

Effect of Shelterbelts on Snow Distribution

In the course of shelterbelt afforestation in Russia and America, an even distribution of snow over the maximum possible distance has been aimed at, in order to control the subsequent melting of the snow and the uniform distribution of this major contribution to soil moisture.

Dense, wide shelterbelts cause an accumulation of snow around the belts, confined to a more or less narrow marginal strip. This may be ascribed to the structure and density of the shelterbelts; snow is caught by dense barriers in great quantity and the turbulence in the lee of a dense shelterbelt may have a considerable effect by leading the snow up against the belt (Vyssotsky 1929).

The drifting of snow is a reflection of the wind velocity (Nägeli 1946, 1953a); this has been generally established. The most uniform distribution of snow is obtained in the shelter of narrow belts which are more penetrable to wind near ground level, although belts which are moderately permeable throughout their whole height may be preferable from other aspects (Gorshenin 1941).

Studies in America (Stoeckeler and Dortignac 1941) have shown that shelterbelts with one or more rows of densely growing shrubs, at least 8 ft high, trapped snow in drifts 5-8 ft deep or more and all the snow was trapped within 30-80 ft on the leeward side of the first shrub row. Narrow belts of pruned trees, penetrable below, allowed snow to sweep underneath and to settle in a thin sheet 1-2 ft deep on the leeward side over a distance of 600-1200 ft. This gave an increase in soil moisture equivalent to a 10-in. rainfall from the fall to the spring, whilst the crop area within 80 ft showed an increase of 5 in. of water. George (1943) also observes that relatively narrow windbreaks of not more than 6-8 rows are more effective than wider belts in utilising snow drifts as a supplementary supply of water beyond that afforded by the annual precipitation. Similarly, it has been observed during heavy snow that well-developed shelterbelts, at least 7 rows wide and with a good shrub layer or a row of coniferous trees on the windward side, trapped all the drifting snow in or close to the plantation. The importance of the shrub layer was shown by a 10-row belt along a highway; it had no shrub layer and caused a 6-ft drift across the road.

Moderately dense shelterbelts at sufficient distance from the edge of a road are to be preferred for protecting road systems (Panfilov 1936).

It is apparent that previous research on snow drifting has been concerned with two totally different aspects: (i) effecting an even distribution of snow over a sheltered region for the purpose of augmenting the water supply in areas of low rainfall; in this case shelterbelts more penetrable to the wind at ground level have been advocated, and (ii) trapping the snow within a narrow zone near the shelterbelt margin to protect lines of communication; for this purpose dense or moderately dense shelterbelts have been suggested. The latter function may have an agricultural application in the protection of grazing animals during heavy snow storms.

A summary of research on snow fences for road protection (Pugh 1950) indicates that solid fences produce drifts on both windward and leeward sides whilst open fences cause drifts mainly on the leeward side. The leeward drift produced by a solid, impenetrable fence is usually short and deep whilst that produced by a penetrable fence is long and shallow. The greater the wind velocity, the closer is the drift to the fence. The solid fence is useful where only limited space is available for the accumulation of snow but investigators in several countries are agreed that the optimum density for a snow barrier is approximately 50 per cent.

"For all except solid fences, the velocity of the wind, up to approximately 25 mi/hr, has no effect on the drift length and, for snow of specific gravity about 0.2, has little effect on the position of the maximum depth. Nøkkentved (1940) states that if the velocity exceeds 27 mi/hr, the drift becomes shorter with increased wind speed but attains a stable form at 34 mi/hr. For a lighter snow, of specific gravity 0.3, wind velocity up to 10 mi/hr has no effect on the drift, but velocities between 10 and 25 mi/hr move the point of maximum depth away from the fence" (Pugh 1950).

These investigations have also indicated that the base of the fence should be elevated above ground level to prevent the fence becoming clogged. This conforms with Gorshenin's suggestion regarding the penetrability of shelterbelts at ground level, as mentioned earlier, although it will cause a reduction in shelter effect for other purposes (Jensen 1954).

Regarding the inclination of snow fences to the vertical, if the inclination is less than 30° the drift is longer and shallower but the cross-sectional area is unaltered; if the inclination is to the windward side there is a tendency for the drift to form on that side (Pugh 1950).

According to German research (Bekker 1947), the drift length (L ft) is related to the fence height (h ft) by the equation:

$$L = \frac{36+5h}{k}$$

where k is a function of the fence density, being unity for a density of 50 per cent and 1.28 for a density of 70 per cent. A further safety margin of 16 ft should be allowed between the fence and the end of the drift calculated by means of the above equation to allow for scatter in the experimental data.

Further benefits of a uniform snow cover in sheltered areas are that protection is afforded to winter crops, the depth of soil freezing is reduced and, in this way, the melting of snow in the spring is more regular and the ground is more receptive to percolation. Surface run-off and erosion are therefore minimised.

Gorshenin (1946) observed that soil freezing is most shallow within the shelterbelt itself and increased in depth with distance from the belt; this could be correlated with the depth of snow covering.

No information is available regarding the optimum width of a shelterbelt whereby the whole of the snow may be trapped within the belt itself, which would appear to be useful information from the point of view of sheltering livestock during heavy storms which are typical of the upland areas of Britain in a severe winter.

Chapter 3

THE ECONOMIC SIGNIFICANCE OF THE INFLUENCES OF SHELTERBELTS

THE MAJORITY of the influences which shelterbelts exert on areas adjacent to them are attributable, directly or indirectly, to changes which they induce in the local climatic factors. The climatic factors are altered not only by the shelter which is afforded by the shelterbelts but also by the living material composing the tree-belts. In addition, there are certain economic influences which are not due to the climatological or biological effects of the belts; these are mainly concerned with the question of land utilisation.

In a consideration of the influences of shelterbelts it is frequently impossible to dissociate those due to microclimatic effects and those ascribable merely to the presence of the shelterbelt as a biological complex and not to its sheltering capacity. For all practical purposes these influences may be discussed collectively.

Interdependence of Climatic and Growth Factors

The main factors of plant growth are light, heat, moisture, carbon dioxide and soil, the last as both a medium for growth and a source of nutritive material. All these factors are affected to a greater or lesser extent by air movement and, thus, by the shelter produced by a windbreak. The light factor is involved through the wind being capable of turning the leaves of plants from their ideal positions, thereby reducing the amount of light utilised (Jensen 1954); in addition, shading by the windbreak will affect the concentration of light. Heat and moisture relationships in sheltered areas have been discussed earlier; both these factors are influenced considerably by shelter and the shelterbelt and are mutually dependent. The carbon dioxide content of the air at the level of plant assimilation is affected by wind and also by temperature. High winds cause a loss of carbon dioxide to higher levels of the atmosphere; increased temperatures promote the production of carbon dioxide in the soil. The influence of wind on the soil is associated chiefly with erosion and the importance of this aspect varies according to the geography of a region. However, in addition, the temperature of the surface soil depends on the relative humidity of the air, the dryness of the surface layers and the temperature of the lower soil layers (Franklin 1919) and therefore on the prevailing wind conditions. By means of its effect on evaporation and the removal of humid air from the soil surface, the wind furthers capillary movement from lower soil layers of water and plant nutrients in solution. It also affects the structure of the soil to some degree.

The interdependence of the climatic factors is extended therefore to those factors controlling vegetative growth. In general, conditions produced by shelterbelts within the area which they protect are found to be more favourable for plant growth.

Effect of Shelterbelts on Agricultural Yields

Many early writers have mentioned the higher

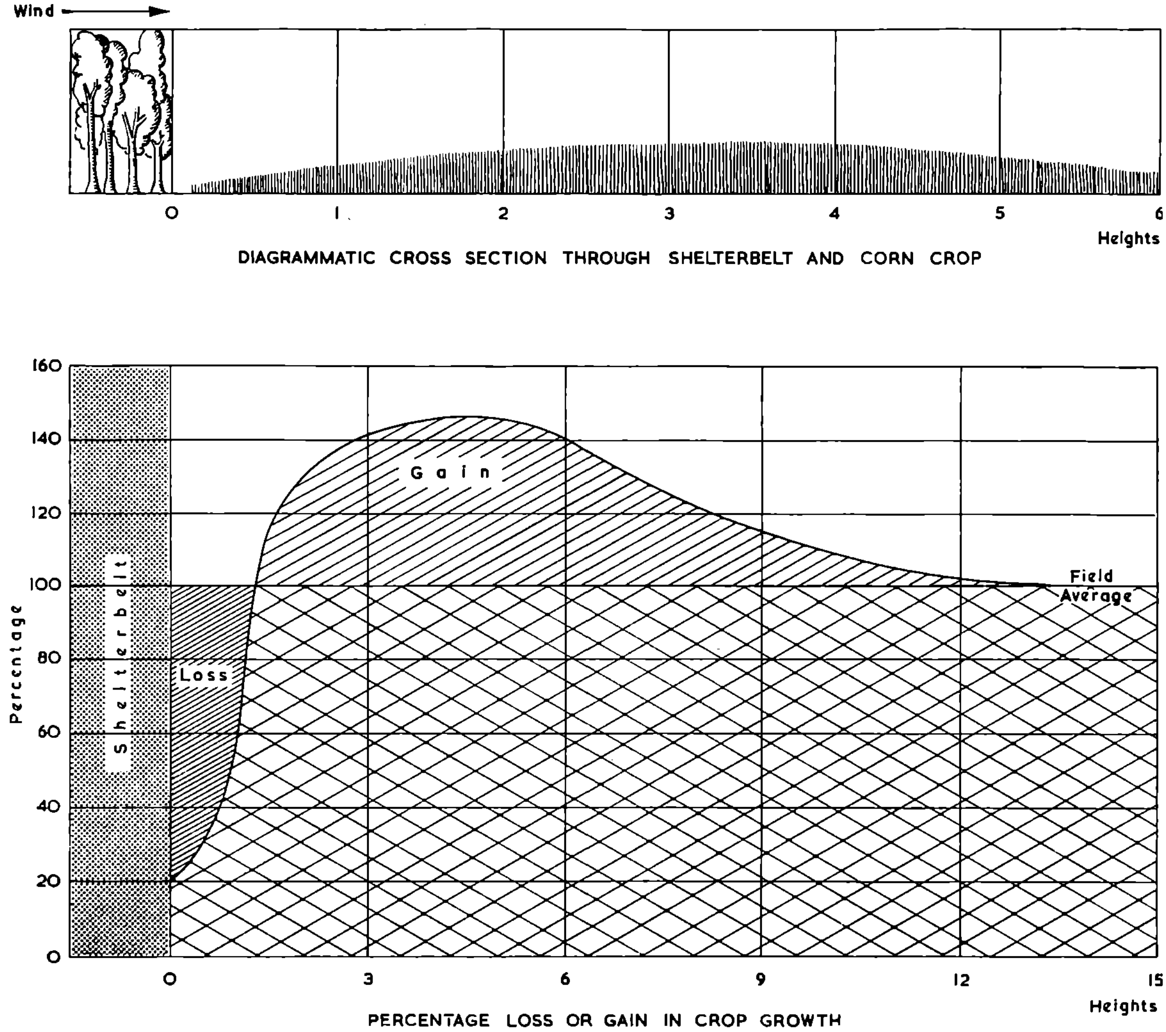


FIGURE 17. Effect of a shelterbelt on crop yields, (after Bates).

crop yields which are to be observed in sheltered areas, the agricultural prosperity which is associated with regions sheltered by plantations, shelterbelts and hedgerows and the decline in productivity which follows upon the removal of such shelter (e.g. Hilf 1951). In order to obtain information regarding the economic value of shelterbelts in raising the productivity of exposed regions, America, Denmark and Russia instituted quantitative investigations of crop yields during the early part of the century. Further investigations have been carried out in this connexion in various parts of the world.

Generally there is a decrease in the yield of arable crops within a narrow strip bordering the shelterbelt, due mainly to root competition and shading. This strip is normally no more than half the shelterbelt height in width. Increased yields extend as far as 12h on the leeward side, reaching a maximum increase of about 45 per cent at 4-5h from the shelterbelt (Bates 1944). These observations were based on crop measurements made in about 25 fields in Nebraska, Iowa and Minnesota in 1908 and in about 50 fields in S. Dakota, Nebraska and Kansas in 1935. In all cases the fields were protected on one side by a shelterbelt. The results are shown diagrammatically in Fig. 17.

Favourable effects of shelter on harvest yields have been reported frequently from Russia: oat yields have been increased by 25-28 per cent due to the shelter provided by a 5-row shelterbelt (Kucheryavyck 1940); hay yields in areas protected by belts were 100-300 per cent greater than those in the open steppe (Ignat'ev 1940). Gorshenin (1941) summarises much of the earlier Russian research on crop yields and relates the increases to improved hydrological conditions in the sheltered areas. In semi-desert conditions shelterbelts have been most effective in raising yields in years more favourable for plant growth than in dry and very dry seasons (Kas'Yanov 1950); not only the quantitative yields of farm crops showed an increase but also considerable qualitative changes were found, the absolute weight per cereal grain being definitely higher in both dry and favourable seasons. The beneficial influence of the shelter was observed in the growth of both sown and naturally growing crops, particularly in those plants most sensitive to wind.

Increases varying from 6 to 34 per cent in root and cereal crops in Jutland have been recorded (Nägeli 1941, 1942), the chief increases being in grass (34%), lucerne (27%) and cereals. Mean yield increases of figures published in the Jutland plant breeding journals between 1908 and 1925 (Andersen 1943) for all cereals are: grain 17.1% and straw 17.2% with West shelter, grain 11.7% and straw 12.1% with East shelter. Other crops showed the following average percentage increases: beetroot 23.2, cabbage crops 13.4, turnips 6.5, potatoes 16.9, grass and clover 24.1, lucerne 21.5, lupins 48.9 (with West shelter); turnips 11.9, potatoes 8.8, grass and clover 23.3, lupins 54.1 (with East shelter). Green-weight yields from grass fields in the rather wet spring of 1913, in fields sheltered on the West, were as follows, expressing the yield at 3h leeward of shelterbelt as 100: 1h - 106, 3h - 100, 5h - 93, 7h - 86, 9h - 82, 11h - 79. In the dry spring of 1914, corresponding figures were: 1h - 66, 3h - 100, 5h - 92, 7h - 89, 9h - 83, 11h - 77, 13h - 76, 15h - 70. In the same spring, fields with shelter from the East produced the following relative yields: 1h - 66, 3h - 100, 5h - 96, 7h - 88, 9h - 80. In conclusion, Andersen states that the increased yield due to shelter is $4\frac{1}{2}$ times as great as the loss in yield due to the location and effect of the shelterbelt on the marginal zone. Studies in Sardinia between 1939 and 1942 on the effects of shelterbelts on cereal crop growth show results similar to the Danish records (Pavari and Gasparini 1943). The increased yields in the sheltered areas compensate for the injurious effects felt over a maximum distance of 10-15 m from the belts (Savi 1949); eucalyptus windbreaks, 10 m high and 30 m wide, caused a maximum yield of grain between 60 and 90 m to leeward and yields superior to those of unprotected areas occurred from 30 m outwards from the belt. For 8 fields over a period of 3-4 years the average increase exceeded 25 per cent.

On an exposed site, where shelterbelts gave protection, potatoes have yielded a 21-24 per cent greater out-turn and it has been concluded that if shelterbelts take up 5 per cent of the cultivated area, which has been considered desirable for German lowland districts, there is a 15 per cent gain if one reckons only on a 20 per cent increase in yield due to shelterbelts (Geete 1944).

Further data on crop yields are given by Wendt (1951), Nicota (1951), Kreutz (1952b), Steubing (1952), Thran (1952) and many other writers. Nicota (1951) records increases due to shelter as 5.2 per cent in the case of quantity and 1.2 per cent in quality.

Much of the research on crop yields has been criticised through not taking into account the varying degree of shelter due to changes in the wind direction throughout the season; in this way no definite quantitative expression of increased production can be obtained for correlation with the degree of shelter experienced during the period of growth of the particular crop under examination (Jensen 1950). By considering the wind-rose for an experimental area and by preliminary investigation of the effect of a scale-model in a wind-tunnel, a percentage "shelter" (wind velocity reduction) value was obtained for all parts of the experimental field, which was enclosed by artificial screens. In the preliminary studies, the parts of the field with little shelter showed yield increases of 5 per cent, whilst those with a greater degree of shelter showed 10 per cent increases. Later observations (Jensen 1954) show a 7-9 per cent excess yield corresponding to 68 per cent shelter and 4.3 per cent increase with 37 per cent shelter. The excess yield is therefore proportional to the degree of shelter.

Significantly greater yields of green and dry matter are to be found under sampling cages as compared with herbage yields in unprotected areas (Cowlishaw 1951). These may be ascribed to changes in micro-environment due to the cages as described by Williams (1951). Similarly, the earlier growth of pasture in the vicinity of shelterbelts, described by Bell (1921) and others, is due to microclimatic changes; this "early bite" is particularly valuable to sheep during the lambing season and after a severe winter. On hill grazings shelterbelts can induce a gradual change to more protein-rich grasses on the belt margins, due partly to changes in the microclimate and partly to more intensive grazing and manuring by cattle and sheep. In certain cases this last factor may cause fouling of the ground and an increase in diseases, such as "worms" amongst the stock, if the sheltered area is used excessively in bad weather.

The protection of orchards by shelterbelts not only reduces wind damage but also extends the ripening season, with consequently higher yields of fruit (Sannikov 1950, Pomaranov 1950). A Swiss market gardener has claimed that the planting of a narrow shelterbelt causes earlier ripening of tomatoes, enabling him to obtain the higher prices obtaining at the outset of a season.

The adverse effect of wind erosion on yields, by the loss of newly-sown crops, fertilisers and top soil (Sneesby 1953), is obvious. Shelterbelts reduce mechanical damage to crops by the wind itself or by sand and fine soil particles driven by the wind (Burvill 1950, Petersson 1947, Kreutz 1952b).

Few writers have mentioned increased yields due to shelterbelts, other than of field and orchard crops. In addition, however, milk yields may be reduced by 16 per cent where grazing cattle are exposed to strong winds (Weir 1947). The resistance of cattle and sheep is lessened by exposure; sheep in sheltered areas make better progress than those on unsheltered pastures and produce a better quality of wool (Cowan 1859). Shelterbelts have been used in the tropics to protect store cattle from drying winds and to guard against the ill effects of exposure to mid-day heat (Foscolo 1949). On upland areas in Britain, shelterbelts allow a longer grazing period on the rough pasture of higher elevations, thereby conserving lower fields for the production of winter fodder.

Many of the effects of the trees in shelterbelts on agricultural crops have been summarised by van der Linde (1953). Trees with spreading root systems are not favoured except where the ground water level is high (Andersen 1943, Dullum and Fich 1947). The problem of weeds which may invade fields from hedges and belts is countered by the argument that, with a balanced woodland vegetation, none of the species will be fit to stand ecological conditions in the cultivated fields in the long run. Trees may act as primary or secondary hosts for insect pests and fungal diseases, particularly "rust" diseases, which are harmful to field crops (Hille Ris Lambers 1948, Schrödter 1952). The migratory aphids are examples of such insect pests. Also, certain insects may show a preference for the microclimate of sheltered regions; this has been investigated in connexion with the relation between aphids and the dispersal of potato virus diseases (Maldwyn Davies 1939). Certain mice prefer sheltered areas (Tischler 1951). Tree belts may harbour birds which prey on arable crops (Boldt and Hendrickson 1952) but the general opinion is that most of the smaller birds which frequent shelterbelts are insectivorous and beneficial to agriculture; many of the worst bird pests do not live in shelterbelts.

Regarding these "edge-effects" of shelterbelts, it is clear that on both sides along a line which separates two different biotypes, the biocoenosis is richer in species as well as in individuals than in other places in the same biotype; this generally holds good for both plant and animal life (Deem 1938, Thornton 1940). The evidence suggests that, after planting a new shelterbelt or series of belts, there may be a transition period during which the biological balance is upset, but this should quickly adjust itself naturally. Obvious mistakes should be avoided initially by means of careful choice of species and planting design.

In an economic consideration of the influences of shelterbelts on agricultural productivity, mention must be made of the occasional as well as the sustained benefits of shelter. In Britain, shelter for sheep is essential in severe winters (McDougal 1953); in the severe winter of 1946-7, it was estimated that 4 million head of sheep perished and a survey of several hill farms in the North of England revealed that 7 flocks which suffered losses of 46-64 per cent were hefted on high, treeless grazings (Stewart and Cresswell 1947). Though lack of shelter was not the only factor contributing to this disaster, it seems that it played an important part. Similarly, in the infrequent use of particular fields for seed production, shelterbelts bordering such fields may reduce cross-fertilisation with neighbouring crops, resulting in greater purity of seed (Jones and Brooks 1952).

That a definite increase in agricultural productivity in areas sheltered by tree belts is to be expected, more than adequately compensating for the loss of the area occupied by the shelterbelts or the narrow zone which may be sterilized by their roots and overshading, has been firmly established in principle. Even losses through shading may be minimised if a strip on the shelterbelt margin is planted with a crop which depends more on the production of foliage than on seed, since the latter requires more favourable conditions (Bates 1911). Local criticism to the effect that shelterbelts complicate mechanised cultivation, in arable areas, and heather-burning (Scots, "muirburn") and shepherding in upland regions can be avoided usually by means of careful planning of the layout of shelterbelts.

Influence of Shelterbelts on Forestry

In considering the importance of shelterbelts in forestry, it is necessary to review briefly the effects of the climatic factors, and particularly the extremes of these factors, on tree growth and on the forest and the extent to which these effects may be improved or accentuated by means of protective belts. In this connexion, the term "shelterbelt" must include any protective strip of woodland designed or adapted primarily to provide shelter or to add stability to a forest block, e.g. a forest margin or an internal windfirm belt.

The general relation between climatic and vegetative growth factors has been discussed earlier and the improved microclimatic conditions in sheltered areas as recorded for agricultural crops must be held to apply also to forest areas similarly protected. Especially significant, however, is the role played by the climatic factors in limiting forest vegetation and, especially, economic forestry and in reducing its productivity on other areas.

The effect of wind on trees is both physical and physiological (McDougall 1941). The physiological effect determines the polar boundaries of forests (Braun-Blanquet 1932) and it has been suggested that it is not the mechanical force of the wind nor cold, salt content and atmospheric humidity which sets a limit to the forest but rather the uninterrupted drying-out of the shoots, lasting for months, at a time when replacement of the water lost is impossible (Kihlman 1890). On the limits of tree growth in the north and at high elevations the physiological drying effect of the wind is always accompanied by mechanical injury and arboreal vegetation shows the combined effect. Kihlman states that, in Swedish Lapland, wind-induced timber lines are characteristic of the isolated flat mountain summits and often run considerably below the forest boundary as determined by temperature.

This desiccating power of the wind, producing the same wilting effects as drought, is increased when the activity of roots is diminished by coldness or freezing of the soil, when the loss of moisture from foliage and branches can not be adequately supplied by absorption (Toumey and Korstian 1947). The height to which plants are able to grow is limited by their ability to transport water upward at a sufficient rate to counteract losses through transpiration; wind velocity usually increases with height above ground and therefore the tallest plants such as trees suffer most from desiccation (McDougall 1941). This explains why extremely exposed places are devoid of tall vegetation and why the trees are smaller on the exposed side of a stand than on the leeward side. The configuration of woods adjoining the coast, the dwarfing and deformation of the windward margins and the gradual increase in height landwards, the uniform slope of the canopy showing the connexion between shelter and growth, are due more to the drying effect of the winds from the sea than to their salt content (Boodle 1920).

The death of plants by winter-killing is very frequently the result of desiccation rather than directly from low temperatures. Thus, plants which are protected from drying winds can endure much lower temperatures than those of the same species which are fully exposed (McDougall 1941).

Continuity of wind action is the factor which most affects the form of vegetation (Braun-Blanquet 1932). Winds with an average velocity of 3-15 m/sec are considered to be the most destructive of vegetation in Central Europe; winds with a velocity above 7 m/sec are capable of destroying shoots that have not yet lignified, whilst developed and lignified plant parts are resistant to a 15 m/sec wind (Int. Inst. Agric. 1929). The deformation of trees by wind on exposed sites is well known and evidence on the relationships between wind-speeds and tree deformation has been recorded (Putnam 1946). Observations of tree deformation and particularly that of the crown may serve as an index of the local wind regime (Weischet 1953, Gloyne 1954). Gloyne suggests that an average annual wind speed of 15 mi/hr or more (ranging from about 12 mi/hr in summer to 20 mi/hr in winter) will result in serious deformation of certain types of trees. It has been stated that the cold regions of the earth must remain treeless wherever the wind, 10 m above ground, attains a mean velocity of 6 m/sec, approximately 13 mi/hr (Symkiewicz 1923-1927).

The physiological action of wind may express itself also in smaller leaves and eccentric growth of the tree-bore as well as in leaning stems and unilateral branching (Warming 1909). The vascular bundles are said to lose their conductivity under the influence of wind, which causes dying and death of the mesophyll (Braun-Blanquet 1932). Wind also reduces the assimilation possibilities of vegetation at

10 m/sec by 70 per cent for light-demanding species and 20 per cent for shade-bearing species (Perrin 1952).

Associated with the limitation of tree-planting by wind is the influence of temperature, particularly the temperature of the four hottest months of the year, generally May-August in the northern hemisphere, or the July mean temperature, which is normally of the same magnitude. The ecological optimum is not the same throughout the whole period of growth of a plant and observations have indicated that the various tree species can live only at temperatures between two extremes, which vary for individual species (Toumey and Korstian 1947). A prolonged low temperature during the growing season is not equivalent to a higher temperature of shorter duration. Where the mean air temperature during the 4 hottest months of the growing season falls as low as 50°F, forests become scrubby in character, whether the temperature results from longitudinal or altitudinal position. A parallel exists between the 10°C July isotherm and the forest limit in the Alps (Lundegärdh 1949) and Perrin (1952) states that the 10°C isotherm and the May-August mean demarcate, in altitude as well as in longitude, the upper limit of forest vegetation which coincides approximately with a growing season of 45 days. Later investigators have observed that tree vegetation is determined by July means of between 7°C for maritime stations and 13°C for continental areas. Helland (1912) verified experimentally the relation between the northern limits of species and the mean growing season temperatures and recorded the following values: 12.6°C for pedunculate oak, 13.4°C for beech, 8.4°C for Scots pine and spruce and 7.6°C for aspen. Rubner (1938) takes as the basis for climatic classification of forest types the number of days when the mean temperature exceeds 10°C (50°F), above which temperature the vegetation is active in all species; this number was found to vary from 60 days at the upper tree limit. In Britain the extent of the growing season for general purposes has been identified with the number of days having temperatures over 45°F.

This evidence suggests that temperature is the chief limiting factor for tree growth but that wind can preclude the existence of forests long before the temperature minimum is reached. It follows that shelterbelts of the most resistant species could extend the areas which are considered suitable for economic planting.

In addition to the restrictions imposed on the physiological processes of tree growth, the climatic factors can exert considerable damaging influences on forest stands. Damage by gales has been stressed constantly in forestry literature. Wind damage results in both economic and silvicultural disadvantages generally. The effect of protective forest margins is recognised in theory as well as in practice (e.g. Troup 1928, Murray 1917, Robinson and Watt 1910, Woelfle 1950, Andersen 1954). Protection strips have also been advised at suitable intervals within blocks of forest (Int. Inst. Agric. 1929, Weir 1953). The silvicultural treatment of margins should aim at stabilising their wind-braking influence which extends to 2-3 times the mean height of the margin trees (Woelfle 1950). Whilst it is not possible to safeguard the forest against exceptionally severe gales, especially those from directions other than that of the prevailing wind, protective shelterbelts should reduce wind damage considerably.

Suitable forest margins can also protect the growing stock from other physical agencies. Sudden exposure of the boles of forest trees having thin bark often results in death of the cambium on the exposed side or "sun scald" (Toumey and Korstian 1947). Troup (1928) has stressed the outstanding importance of the sun as a factor adverse to the establishment of natural regeneration under certain conditions by drying-up the soil and causing high mortality amongst seedlings. Insolation also hastens the decomposition of organic matter and may render soil conditions unfavourable for natural seeding. Removal of leaf litter by accelerated decomposition or by wind may further cooling of the soil at night and increase the danger of spring frosts (Franklin 1920). Hall (1913) has recorded the better condition of young spruce where sheltered by a quantity of natural birch on a margin. Dew is a beneficial factor in a regeneration area and prevents mortality amongst seedlings through desiccation (Troup 1928); dewfall is considerably higher in sheltered areas than in the open (Steubing 1952).

The benefits of shelterbelts to forestry may be summarised as follows:

(i) The use of shelterbelts may allow the planting of areas which are otherwise too exposed for economic forestry. This practice would facilitate establishment of the forest; Petrie (1951) has recorded the silvicultural desirability of establishing marginal and internal belts of wind-resisting species some years before the planting of the main species, with the object of having a certain amount of shelter in readiness.

(ii) Microclimatic conditions produced by shelterbelts within their zone of influence are generally more favourable for the growth of trees; possible disadvantages such as frost may be minimised by means of penetrable belts.

(iii) Protective margins and internal belts will reduce damage by strong winds and promote forest conditions more favourable for regeneration immediately behind the plantation margins.

(iv) Shelter margins, designed specifically for protection, should occupy a smaller area than would normally be occupied by deformed and retarded trees if the main timber species were planted right to the edge of the forest area; this would imply an increase in the productive area of the forest (see Robinson and Watt 1910).

It would appear that, as with agriculture, so the productivity of forest areas should be significantly increased by the establishment of shelterbelts. The majority of the possible disadvantages cited in the case of agricultural yields, e.g. shading, root competition, birds and insect pests, should not apply under forest conditions.

Further Economic Advantages and Disadvantages of Shelterbelts

Any scheme of land reclamation or improvement involving increased productivity of agricultural, horticultural and forestry industries must have a decisive beneficial effect on rural and national economy. The social and economic effects of the American Great Plains shelterbelt project in terms of soil and human betterment have developed gradually (Durrell 1939). Similar evidence is to be found in connexion with the rehabilitation of the steppe regions of Russia and the Ukraine (Gorshenin 1941, Sus 1936 and 1944, Zon 1949), the reclamation of the Danish heathlands (Andersen 1943, Basse 1935, van der Linde 1952) and of the Orbe plain in Switzerland (Grivaz 1954). There are many other examples of increased prosperity achieved on exposed areas and made possible through comprehensive schemes of shelter planting. In such cases, the advantages of shelterbelts far outweigh the disadvantages and opposition from the local community on the grounds of loss of agricultural area to trees is quickly overcome (Hilf 1951).

In the economy of the individual farm, shelterbelts enhance the property value in spite of the reticence of many property owners to undertake further planting. Belts also produce a certain amount of fuel-wood and minor produce suitable for farm use. It has been suggested that they may save up to 40 per cent of the fuel costs on an American prairie farm (Bates 1945). Disadvantages, apart from the initial cost of establishment, are concerned mainly with the losses in agricultural field crops which may occur on the marginal zone of the shelterbelt; such losses are more obvious than the higher yields in the remainder of the sheltered area and the latter may be overlooked. A further possible disadvantage is that cereal grown in sheltered areas will grow faster and have longer straw, the strength of which will be diminished; Jensen (1954), after investigations of this factor, observes that, even if the strength is less in proportion to the straw length, the risk of breakage in wind will normally be less in sheltered regions. In winds from an unusual direction, however, laying of crops may be more serious within the zone of influence of a shelterbelt than without. The criticism that shelterbelts require periodic treatment to maintain their optimum degree of penetrability, this being beyond the capabilities of the farm staff, can hardly be considered a disadvantage.

From the hill farm aspect, it has been suggested that shelterbelts on hill grazings will result ultimately in a less hardy type of animal, particularly in the case of sheep. However, there is little scientific evidence to support or contradict this suggestion. On the other hand, these is considerable evidence to the effect that shelter planting on hill land can, lead to greater intensification of land use.

With reference to the application of shelterbelts to forestry, it has been observed that economic and administrative conditions may not allow the prior planting of protective belts on areas scheduled for afforestation (Petrie 1951). Evidence in favour of protective belts and wind-resistant forest margins has been collected mainly as a result of damage by gales and little information is available as to their practical and economic use from the time of the initial planting. Obviously shelterbelts in forestry will complicate management problems to some extent, probably involving the employment of two distinct working circles in a plan of management, but silvicultural technique should be simplified or made somewhat easier and the climatic evidence reviewed earlier would appear to imply a greater return from the forest which is adequately protected by marginal and internal belts.

In all cases the capital investment required for establishment of shelterbelts, particularly if expensive fencing is essential, would appear to be the only major economic disadvantage. In forming shelterbelts for the protection of arable land the considerable research data available on increased yields show that this initial expenditure produces adequate compensation within a short space of time. On hill land, excluding the protection of grazing stock during severe storms, similar returns are less easily recognisable but may be expressed in the survival rate or general progress of lambs, for example, in an average season (Wilkie 1890). In both instances, the use of land for shelter planting has been proved to be justifiable. The economic factors regarding shelterbelt employment in relation to forestry, particularly with respect to their use preparatory to afforestation, would appear to require further clarification.

Chapter 4

GENERAL CONCLUSIONS ON SHELTERBELT TYPES, LAYOUT AND STRUCTURE

THE MAJORITY of published observations and research evidence on suitable designs, types and structures for shelterbelts concerns plateau areas. There is little information regarding shelterbelts in regions of irregular topography. However, certain inferences applicable to both requirements can be drawn.

In order to protect the maximum area, the axis of a shelterbelt should be, as far as possible, perpendicular to the direction of the prevailing or other wind against which protection is required. When the wind strikes a shelterbelt obliquely, the sheltered zone is reduced according to the angle of incidence of the wind (Gorshenin 1941). In some regions the prevailing wind may be more or less constant in direction; in Britain, the prevailing wind direction must be considered as a mean of directions within a certain range centred about a "prevailing" direction and it is possible, even in fully exposed sites, that the wind may not blow from this "prevailing" direction as much as 50 per cent of the time (Gloyne 1954). The prevailing wind may not be the most damaging wind in some regions; frequently areas in Britain where the prevailing wind is south-westerly may suffer from cold, dry, easterly or north-easterly winds at critical periods in the agricultural, horticultural and forestry seasons.

As the wind approaches a shelterbelt, there is a tendency for the direction to be deviated along the belt margin, although the evidence appears insufficient for quantitative statements to be made (Gorshenin 1946, Woelfle 1935 and 1936, Nägeli 1946). However, with deviations from the normal of up to 45° the protective effect, for all practical purposes, is reduced only slightly and some latitude is permissible therefore in orientation of the shelterbelt (Gorshenin 1946).

Shelterbelts with an E-W axis should be avoided as far as possible, especially in arable districts, in order to minimise the harmful effects of shading or insolation on the respective sides of the belt.

For full utilisation of the distance protection, shelterbelts should be 12 times their height in length and to cater for winds varying through 90° the length should be 24 shelterbelt-heights (Bates 1944). Nägeli (1953a) suggests that for maximum efficiency belts should be 11½ heights long at least and mentions the probability that bending the ends of the belt in a leeward direction in rounded or angular form might lead to an extension of the sheltered area laterally although this might be achieved in exceptional cases only.

Regarding the optimum spatial arrangement of a series of parallel shelterbelts, the available research information does not allow general conclusions to be made. Woelfle (1938) has suggested 250 m between belts intended to reach 15 m in height, with intermediate hedges 4-5 m high, so as to provide 30-40 per cent shelter in the enclosed area. In practice, single-row belts, 5-7 m high, are planted about 100 m apart in Denmark; in Canada, distances between belts of 165-220 yds have been recommended (Walker 1946); in Germany, an interval of 12 heights has been suggested (Olbrich 1952); in Russia, it is considered advisable to space longitudinal belts at distances equal to 25 times their height, but this distance may be varied according to the type of soil and its liability to erosion (Gorshenin 1941); on the Orbe plain in Switzerland, the distance between belts varies from 600 to 700 m. In laying out a system of shelterbelts the ultimate height, based on local growth conditions of the species, should be borne in mind so that the eventual sheltered zone can be traced and the spacing adjusted accordingly (Nägeli 1946). On slopes liable to erosion the distance between belts may require to be less than on level ground (Gorshenin 1946).

On plain areas 8½ acres of shelterbelts are considered sufficient to protect a 165-acre farm. This implies devoting approximately 5 per cent of the total area to shelterbelt planting; this proportion seems to be generally accepted as desirable (Geete 1944, Olbrich 1949).

For maximum efficiency, i.e. to shelter effectively the greatest area, shelterbelts should be moderately penetrable to the wind throughout their height, except where it is desired to achieve uniform distribution of snow within the sheltered area during the winter. In this case, the shelterbelts should be slightly more penetrable near the ground. The optimum degree of penetrability is between 30 and 50 per cent. The Russian "latticed" construction, which is designed to provide moderate permeability, allows the main portion of the wind currents to pass through the belt without changing their direction, the trees acting as a filter rather than a barrier. In practice, narrow belts of 7 or fewer rows, and even wider belts with evenly distributed, narrow, vertical openings running longitudinally, may be referred to this category (Gorshenin 1941). Danish research (Nøkkentved 1938, 1940) indicates that single-row shelterbelts (or, more precisely, hedgerows) of leaf-tree species and particularly hawthorn (*Crataegus oxyacantha*) and Swedish whitebeam (*Sorbus scandica*), the former being kept clipped in early years and then cut back laterally at intervals of several years, most nearly approach the ideal porosity. However, their protective efficiency is reduced during the leafless period and the shelter effect in summer is 21 per cent greater than in winter.

The moderate degree of penetrability implies the use of narrow shelterbelts although the difficulty of maintenance and establishment generally precludes single-row belts and multiple-row shelterbelts are preferred. The width of a shelterbelt is determined frequently by the availability of land and its value and, in exposed areas, by the degree of exposure and its relation to growth factors. In some cases, narrow shelterbelts are impracticable. On Russian arable areas, belts of 5 rows (7.5 m) and 7 rows (10.5 m wide) are customary, the spaces between rows being increased from 1.5 m to 2.3 m where mechanical tending is employed (Gorshenin 1941); on slopes, contour belts of 7 tree rows with short transverse belts, not more than 1 km apart, of 2-4 rows widely spaced are advocated (Gorshenin 1946). In the American prairies, 10-row belts, 90 ft wide, are conventional but narrower belts of 7 rows (60 ft), 5 rows (40 ft) and less have been recommended in certain areas (Woodruff and Zingg 1953); Weir (1947) quotes 16-row belts of 132 ft in width as typical. In Switzerland, agricultural shelterbelts, 10 m wide, feature prominently in the Orbe plain with others 20 m wide (Grivaz 1954); in the Rhine valley three categories are suggested (Fig. 18), these being 10-15 m, 5-10 m and 2-5 m in width (Tanner and Nägeli 1947). In Germany, belts intended to reach 10-20 m in height must have 3, 4 or 5 rows; 3 rows are sufficient for strips 10 m high but 5 rows at least are necessary for 20 m high belts (Olbrich 1952). The higher the belt, the more rows of trees are normally required since with increase in height there is a tendency for belts to become more open and the gaps left by large trees may be a serious disadvantage in a narrow shelterbelt.

Recommendations of width for upland, pastoral districts in Britain vary. Weir (1947, 1953) suggests 2½ chains, Cadman (1953) 2 or 4 chains, Guillebaud (1943) 2½-3 chains. These widths have been suggested with the intention of a certain amount of timber production. An experimental belt of 19 rows, 1½ chains wide, has been planted in a very exposed district in N. Scotland but the degree of success can not be assessed at this stage (Zehetmayr 1952). It follows that belts designed for timber production must aim at greater widths and a lower degree of penetrability than normally advocated. However, for the shelter of livestock, as opposed to ground area, the dense barrier may be more efficient than a permeable one (Gloyne 1954).

Regarding the most suitable cross-sectional profile for a shelterbelt, no definite conclusions are possible. American studies (Woodruff and Zingg 1953) have suggested profiles rising from 7½ ft at the windward edge to the maximum height of 30 ft at the 7th row in a 10-row belt, the 5th row in a 7-row belt and the 4th row in a 5-row belt (see Fig. 11, Designs C, E and F). The first case, the 10-row belt, implies a slope in the upper canopy of 20° approximately.

Little information is available regarding the siting of shelterbelts in upland areas, except that belts should follow local topographic changes such as spurs and ridges (Gorshenin 1946); protective belts on arable slopes up to 8° in practice have the same sheltering efficiency as those on level ground. Cadman (1953) has suggested planting a shelterbelt in the lee of a ridge where the wind is severe, from the point of view of facilitating establishment of the belt. It would appear, however, that its effectiveness will be reduced in such cases and belts are more effective on windward slopes or at the top of ridges (Blenk 1952). Leeward slopes below 8° are assumed to be unprotected (Woelfle 1950) and only on steeper slopes will this question arise. Since the shelter behind a hill is restricted to a short distance and is followed by a region with increased wind speeds (Woelfle 1937), it may be supposed that a shelterbelt would require to be situated beyond the naturally sheltered zone but on steep slopes there would be a possibility of the belt being overflowed and its area of influence curtailed.

The selection of species and planting design must depend on the local soil, climatic and growth conditions and few general principles may be listed. A fairly composite mixture of leaf-trees is preferred usually to pure conifer belts, both from the aesthetic point of view and the fact that the latter are excessively dense in youth, after which they thin out too rapidly and are difficult to regenerate. With leaf-trees it is more easy to regulate their efficiency and the fact that they lose their leaves in winter is advantageous, in arable districts, since it enables uniform distribution of the snow (Nägeli 1946). However, where shelter is required all the year round, an admixture of coniferous trees or other evergreens is essential even though this may consist of only one row on the windward side of the shelterbelt as suggested by Grivaz (1954). An echelon arrangement of the trees is considered advisable (Olbrich 1952).

Continuity of the shelter is essential and the ultimate means of regeneration must be borne in mind at the outset. For this purpose it is desirable for the established belt to be uneven-aged (Cadman 1953). This may be arranged by strip-planting, half

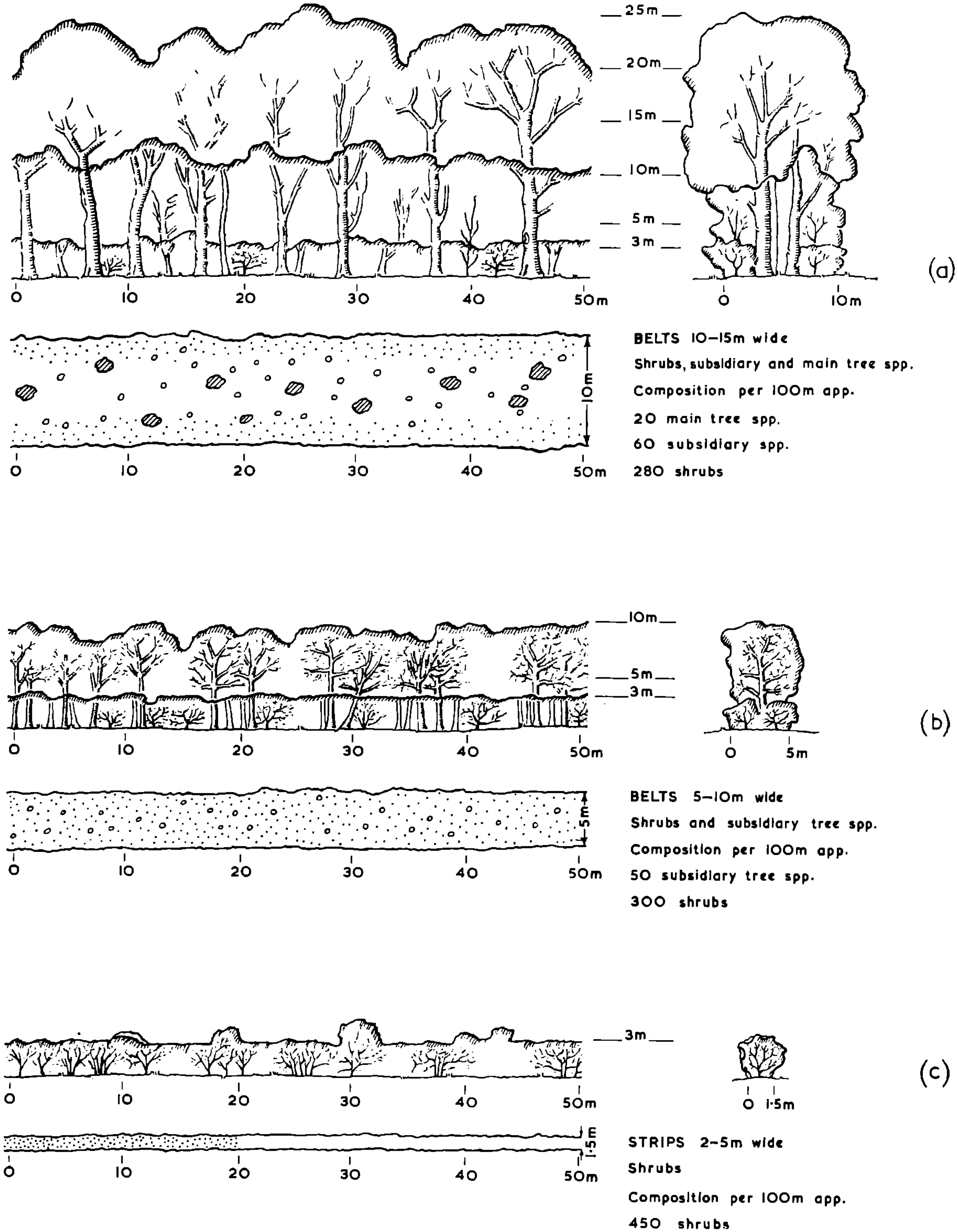


FIGURE 18. Scheme of shelterbelt types, St. Gallen Canton, Rhine Valley, Switzerland, (after Tanner & Nägeli).

the width of the shelterbelt being planted initially and the remainder mid-way in the rotation (Hilf 1951) or by planting the whole area at once and, after a heavy thinning, underplanting and interplanting. A third possibility would be staggered planting, probably in groups, over the whole area but this practice would involve delay in achieving the initial shelter. Management on a group selection or selection system would appear to be preferable for maintenance of permeability and regeneration. There is as yet no evidence as to the desirability or otherwise of a uniform profile and a straight upper edge in elevation.

In some areas the species selected for initial planting may of necessity be a pioneer species to enable the later introduction of a more valuable shelter species. Wide espacement of trees may be used in the first planting operations for this purpose. A characteristic of many young shelterbelts in Switzerland is the selection of one fast-growing species, such as poplar and willow varieties, in order to give height to the belts as quickly as possible; frequently such species are planted some distance apart within one or two rows only and interplanted with secondary species such as alder and birch.

The Russian authorities have issued comprehensive planting instructions for the main soil types in the steppes, according to the structure of shelterbelt required. In 1940, fundamental bases of construction were laid down (Gorshenin 1941) as follows:

(i) Penetrable below, complete above, with no underwood, generally of 5 rows.
(ii) Penetrable below, complete above, with a low-growing underwood, generally of 5 rows.
(iii) Equally penetrable from top to bottom or "latticed", with not more than 20 per cent of "latticing", generally of 5 or 7 rows.

Fig. 19 shows the relative wind velocity abatement by several shelterbelts, based on investigations in Switzerland (Nägeli 1943, 1946). It can be seen that the four most effective shelterbelts, from the point of view of distance protection, are the Epinette leaf-tree belt, the old spruce belt at Riedthof, the young spruce belt at Riedthof in the winter condition and the Furthtal leaf-tree belt in summer, in that order. These belts may be described briefly as follows:

Epinette Leaf-tree Belt: Planted in 1911/1912 with Canadian poplar, Weymouth pine and Norway spruce for the most part, with a spruce/ash mixture in the north-east, and throughout an admixture of other hardwoods, notably oak, beech and Norway maple, the belt is 600 m long and 75 m wide in the centre part. During the measurement of wind velocity recorded in Fig. 19, the belt was traversed at a width of 90 m. The overall average height was then 20 m, the poplars averaging 26 m and attaining a maximum height of 28 m and other species 8-20 m. The belt appears dense and from the interior presents the appearance of closed, high forest. Andreae (1953), records figures of timber yields from this belt.

Old Spruce Shelterbelt, Riedthof: This belt is 150 m long and about 17 m, wide and at the time of investigation was described as having one complete row of spruce on the leeward side and two rows of younger 15-year-old spruce on the windward margin, the inner portion being composed of a vigorous stand of oak, elm and poplar and with a large variety of shrubs. The average height was 16.5 m.

Young Spruce Shelterbelt, Riedthof: This belt is composed of 3-4 rows of spruce with a profusion of shrubs and small tree species particularly on the leeward side; the average width is 3 m. At the time of measurement the average height was recorded as 6.8 m. The belt is dense in summer but somewhat more penetrable in winter.

Furthtal Leaf-tree Belt: This remnant of a former wood has an average width of 15 m and when studied had an average height of 16 m. It consists of a mixture of pedunculate oak, hornbeam, cherry and scattered larch in the upper canopy with ash, lime, sycamore, field maple, aspen, spruce, silver fir, hazel and blackthorn in the lower storey and underwood and a variety of shrubs on the margins. The belt presents a fairly dense appearance.

The above examples, though seemingly fairly dense, are apparently moderately penetrable to the wind.

The requirements of shelterbelts for arable farming districts in Britain may be considered similar to those in Switzerland, America and Russia fundamentally. For upland grazing areas requirements may be somewhat different. Regarding shelterbelts and protective margins for forests, there is insufficient evidence for definite inferences to be drawn in relation to structure and design.

For protection of newly-afforested areas a shelterbelt would require to be moderately penetrable to the wind since the requirements of the young trees would be similar to those of agricultural crops as regards micro-climatic factors and their amelioration.

Protective margins of wind-resistant species should be twice the height of the stand in width and corners should be strengthened with a margin of 6 tree-heights in width (Woelfle 1950). Andersen (1954) suggests that a margin probably requires to be 100-150 ft wide to give effective protection. During the gale damage in Scotland in January 1953, plantations showed that the common practice of planting one or a few rows of beech along the edge exhibited a favourable influence for 50-100 ft but there were instances where stands behind a few widely-spaced broadleaved trees showed wedgeshaped areas of damage, either originating between the trees or in a gap. Andersen states further that apparently no partial shelter effect is provided by a lower stand to windward, but on the contrary an increase in wind speed or gustiness takes place immediately above its crowns; this would appear to indicate that the margin of a forest should be of approximately the same height as the rest of the stand. On the other hand, an earlier statement is quoted to the effect that the artificial production of a sloping canopy by top-cutting the trees on the windward margin gave beneficial results. The evidence furnished by coastal shelterbelts and woodlands would appear to confirm that a gradual, uniform slope in the crown level from the windward edge affords considerable protection to the stand behind. No general conclusion can be drawn for the prevention of damage to forests which frequently occurs some distance behind the margin, the latter remaining undamaged (Woelfle 1950, Andersen

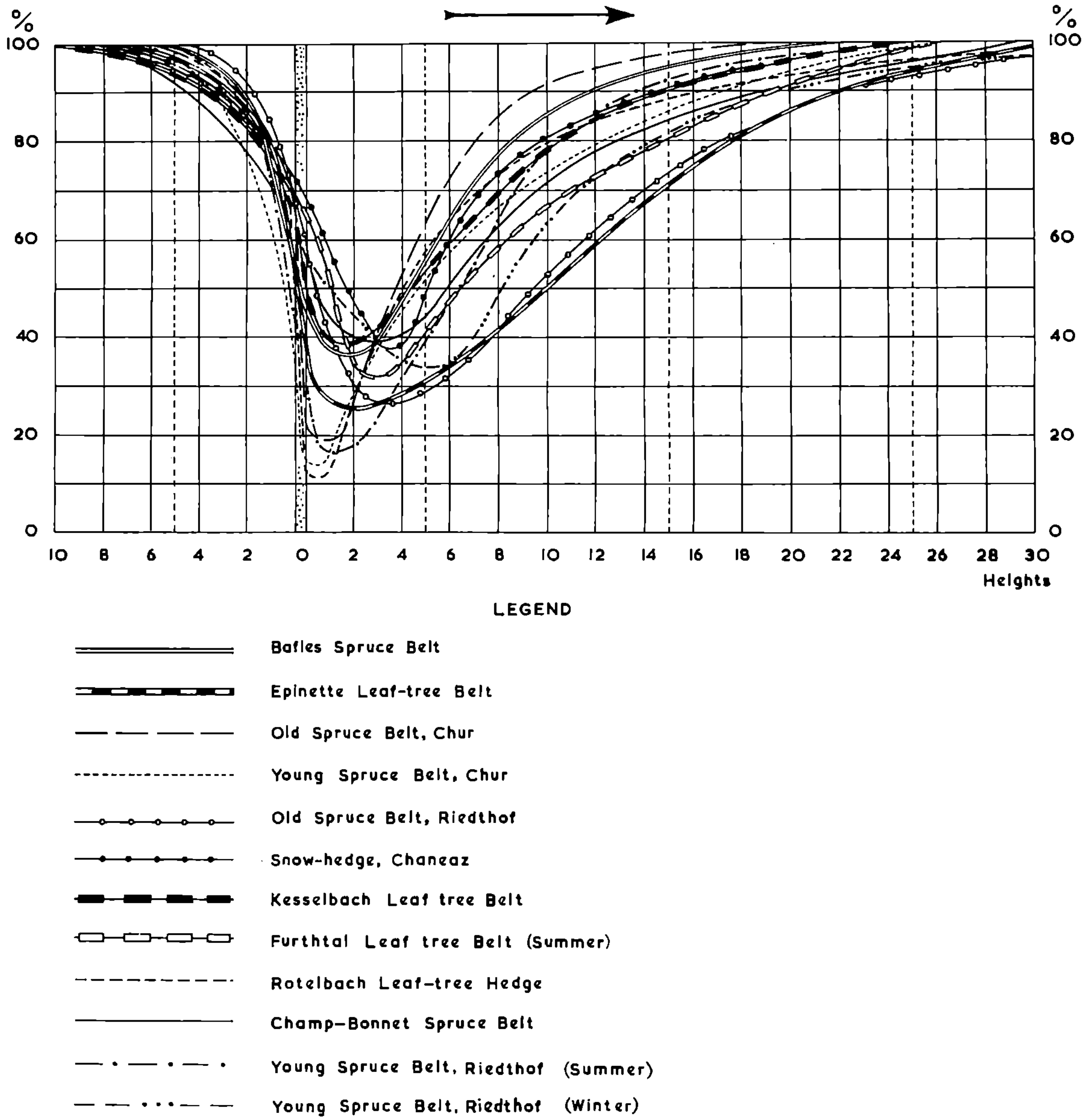


FIGURE 19. Relative wind velocities in the vicinity of 12 shelterbelts, (after Nägeli).

1954) but it may be assumed that a dense marginal belt will produce considerable turbulence behind it and it has been suggested that margins should be kept reasonably open so that the wind does not meet a solid wall of resistance (Dalgleish 1953). Marginal trees which are free to move their crowns also develop a greater resistance to wind-throw (Woelfle 1950).

Internal protective belts should follow natural boundaries as far as possible and should enclose units of 5-10 acres, protecting them individually; there is ample evidence that these have been an important factor in protection (Wagner 1923, Woelfle 1950). Macdonald (1952) suggests a strip system of planting conifers in regions exposed to strong winds; such strips might be 1 or 1½ chains wide, planted on a cycle of 10 years.

Plantation margins should be kept fairly straight and re-entrants should be avoided since they form funnels for the wind. Woelfle (1950) explains that a re-entrant in the margin causes two deflected streams in the wind and these meet at the apex of the wedge; since the pressure at this point is approximately equal to the square of the combined velocities of the two streams damage is usually considerable and may extend some distance into the forest. At the end of such a "blown" area, a new margin is created which is not adapted to wind; thus, further wind damage is inevitable.

On very exposed areas, it may be advisable to construct a wind "chimney", i.e. to clear or leave unplanted an open space of adequate dimensions in the direction of the wind, sufficiently extensive to draw off the wind and prevent damage to the stand (Int. Inst. Agric. 1929).

For purposes of protection on margins leaf-tree species are considered to be most suitable since they are capable of withstanding higher wind pressures usually and, whilst their crowns may be sensitive to exposure, they possess greater adaptability to the wind and normally exhibit reasonable height growth in exposed situations.

PART TWO

CONSIDERATION OF RESEARCH PROCEDURE

Chapter 5

PREVIOUS RESEARCH AND ITS APPLICABILITY TO REQUIREMENTS IN GREAT BRITAIN

RESEARCH activity in connexion with the effects of shelterbelts on microclimate and rural economy and their practical employment has been concentrated mainly in regions where reclamation or rehabilitation of agricultural land was imperative, usually on dry windswept plateaux such as the American prairies, the Russian steppes, the Dutch and Danish heathlands and the valley plains of central Europe. In most cases erosion control, conservation of soil moisture and amelioration of climatic extremes have necessitated shelter planting on an extensive scale.

The situation in Britain has developed differently. The geographical position of the British Isles has precluded the extremes typical of continental climates; few areas in the country are subject to continuous drought and the general topography and landscape pattern have served to maintain a reasonably high degree of shelter from wind and weather, particularly in the primarily arable districts. Marginal and submarginal land improvement has fluctuated with agricultural prosperity and periodic necessity; land betterment projects involving large areas have been relatively few and developments carried out by individual landowners during the past two centuries have passed from general recognition. At the present time, however, a large proportion of the land surface capable of further development lies in exposed upland districts and it would seem that consideration of the shelter planting question, whilst including in its range the possibilities of improving existing agricultural and forestry areas, should be directed chiefly towards amelioration of these upland areas for stock-rearing and afforestation. The value of shelterbelts, demonstrated elsewhere, suggest that their scientific employment in this country can contribute materially to the intensification of land use, which becomes a matter of increasing importance.

Probable shelter requirements under British conditions may be classified as follows:

(a) Agricultural—
- (i) shelter for arable areas;
- (ii) shelter for upland pasture;
- (iii) shelter for stock on exposed grazings;

(b) Forestry—
- (i) protection of established forests against wind and other atmospheric influences;
- (ii) shelter against, and amelioration of, local climatic conditions on areas scheduled for afforestation.

In providing shelter for arable fields, upland and hill pasture and new forest areas it will be desirable economically to achieve the maximum distance protection consistent with an efficient degree of shelter near the ground. The protection of forests implies the safeguarding against storm damage and other atmospheric agencies at all levels from the ground to the crown surface. For sheltering stock on exposed grazings, and not the pasture itself, it may be necessary to sacrifice distance protection for a higher degree of shelter within a restricted zone near the shelterbelt, particularly in areas subject to severe snow storms.

The application of shelterbelts to lowland arable areas in Britain and their resultant effects may be considered similar to the situation in arable regions elsewhere, apart from variation due to different microclimatic conditions. In all cases, the fundamental objective is abatement of wind velocity in order to improve agricultural productivity and protect the soil. Conclusions established experimentally in America, Russia, Denmark and Switzerland, for example, may be considered applicable to cultivated farmland in Britain to a very large extent. These comprise general rules for the orientation, length and spatial arrangement of shelterbelts and the theoretical optimum degree of penetrability to be achieved. Structures and designs of shelterbelts, recommended for these countries, may be used as a basis for the construction of similar belts in this country but considerable variation is inevitable, due to the different availability of tree species, the diversity of their form and habit in different localities and the changed climatic conditions. Scientific investigation of existing shelterbelts and their influence on microclimatic factors, particularly wind velocity reduction, would allow a general classification of the utility of different belt structures and composition by species, in terms relevant to domestic conditions and requirements although local variation might be expected to occur more frequently in Britain than, for example, on extensive uniform areas of steppe and prairie.

Since conservation of soil moisture and uniform distribution of snow in arable fields are not likely to display such great importance in this country, it would seem probable that the associated effects of shelterbelts on microclimate and not merely on wind velocity abatement will necessitate variance from place to place, for economic reasons, in the optimum degree of penetrability of tree belts according to local climatic and edaphic factors. As with the majority of field data available, statistics of increased crop yields in sheltered areas, as obtained in America, Russia, Denmark and elsewhere, must be adjudged a guide to, rather than a criterion of, similar increases to be expected in Britain.

In arable districts the width of shelterbelts in the direction of the wind is governed usually by the area of ground which can be spared economically for tree planting and the minimum width necessary for maintaining the required degree of shelter. In upland districts it would seem reasonable to assume that the proportion of ground area available for shelter planting would not be so limited. Although increased width of shelterbelts implies a lower degree of penetrability to the wind and, consequently, a decrease in distance protection, previous research does not furnish conclusive evidence on the part played by width on the pattern of air flow or on the sheltered area leeward of wide plantations. The question of shelter planting in upland districts is further complicated by economic considerations and the natural tendency to combine the provision of shelter with some form of timber production in an attempt to offset high fencing costs.

Regarding shelter for stock, chiefly confined to exposed grazings, there is little physiological evidence as to the type of shelter required from the point of view of the comfort and well-being of the grazing animal but it may be supposed that shelter from blizzards and cold drying winds, particularly when the animal is wet, is most important. Therefore, maximum reduction of wind velocity may be desirable for occasional shelter; there is ample evidence that this may be obtained by means of a dense or fairly dense shelterbelt.

Information regarding protective margins and internal wind-firm belts for forests is limited and consists mainly of observational evidence of gale damage to forests when wind conditions were extreme and not easily understandable afterwards. The pattern of air flow over and through a forest at varying velocities requires further clarification.

It is obvious that the comparative study of shelterbelt effects becomes more complicated and difficult in hilly country and influences recorded with respect to shelterbelts on level plateaux must be considered as the ideal for regions of irregular topography rather than the actual. Since the majority of research results published concerns plain districts, these findings can be correlated and general implications drawn regarding effects on microclimate. However, the variables involved in measurement of climatic factors under natural conditions frequently render such comparisons difficult, a fact which has led to the investigation of certain basic shelterbelt features in the laboratory.

It is rarely possible to isolate any one of the basic dimensions of a shelterbelt, height, width, length and penetrability, in nature. These variables can be isolated completely, however, by means of experiments with artificial windbreaks either in the field or in a wind-tunnel, as carried out in Switzerland, America, Denmark and Germany. Although it is argued that wind-conditions in nature are incapable of being reproduced in a wind-tunnel, there is no doubt that the comparative study of any one variable factor under such ideal conditions must allow a practical application in nature. As a result of such studies, the evidence of the role played by the height of the shelterbelt in determining the extent of the sheltered area and, similarly, the degree of penetrability of the barrier, may be regarded as conclusive. The relation of the length of the shelterbelt to the area of shelter is apparent from model experiments in the field. Although translation of some of this evidence to natural shelterbelts is difficult, e.g. the evidence of the optimum degree of penetrability obtained by wind-tunnel studies, it is the qualitative rather than the quantitative result which must be considered of practical value and this must be held to obtain ideally under natural conditions.

To summarise, previous research has established certain general principles of shelterbelt design and layout applicable to requirements in Britain, particularly those of lowland arable areas. For upland regions more evidence is necessary concerning the pattern of wind flow in areas of undulating topography from the point of view of siting shelterbelts for maximum efficiency. Economic considerations demand the investigation of shelterbelt width and its relation to the sheltered area. In this connexion and from the aspect of shelter for forest areas, more information on suitable cross-sectional profiles for shelterbelts is desirable. The recorded effects of shelterbelts on microclimatic factors have a qualitative application to conditions liable to be encountered in Britain, but further investigation is desirable in relation to domestic requirements. With regard to the technique of shelterbelt application and maintenance, a method of estimating the efficiency of individual belts is necessary in order to regulate their effectiveness by appropriate silvicultural treatment. The employment of shelterbelts and protective marginal strips in forestry practice requires detailed study of the microclimatic implications.

Chapter 6

INSTRUMENTATION AND EXPERIMENTAL TECHNIQUE IN PREVIOUS INVESTIGATIONS

RECORDED investigations of the effects of shelterbelts on microclimate have been conducted both under natural conditions and in the laboratory. Field studies have involved measurement of the various climatic factors in the vicinity of living treebelts as well as artificial barriers or screens. Laboratory investigations have been concerned mainly with wind- and water-tunnel experiments employing model-scale windbreaks. Methods of working and instrumentation have shown considerable variation, particularly in field experiments, and frequently research papers have failed to give adequate details of experimental technique, thus rendering analysis of results with a view to their practical application generally both difficult and unreliable.

Reduction of wind velocity within a certain area, being the primary effect of any natural or artificial sheltering object, has been investigated more thoroughly than other physical factors of the microclimate, although a number of secondary effects, frequently of greater interest from an agricultural aspect, e.g. increased crop yields in sheltered areas, have probably received the most detailed attention by research workers.

Instrumentation and methods used for the assessment of microclimatic factors may be summarised as follows:

Section 1. Field Investigations

A. INSTRUMENTATION

(i) Wind Studies

Smoke has been used frequently to demonstrate the pattern of air flow in the vicinity of shelterbelts and artificial windbreaks (Woelfle 1935-9; Nägeli 1953a) and, more recently, in the investigation of light winds, soap bubbles timed with a stop-watch (Zentgraf and Eisenkolb 1952). Generally, however, research workers have required more reliable quantitative measurements of wind velocity and direction and mechanical or electro-mechanical anemometers have been employed.

Anemometers of the cup-rotor type have been most commonly used. Bates (1911) used "the standard anemometer", presumably of the cup type. Nägeli (1943, 1946, 1953a, 1953b) employed 18 small portable cup-counter instruments, which it is understood were manufactured for the Swiss army by Prof. Kreis in Chur. These anemometers consisted of a rotor bearing four hemispherical cups on short arms, activating a simple counter with a five-figure dial, the "drum" of the last numeral being graduated horizontally in fifths of a unit. With a low starting speed of 0.25 m/sec and simple, robust and weatherproof construction, without the added complications of on-off switches and set-to-zero mechanism, this would appear to be a most practical instrument. van der Linde and Woudenberg (1951) used a small cup-anemometer with a counter mechanism similar to that employed in British vane-anemometers or airmeters. Gorshenin (1946) records the use of 70 Fuess anemometers, details of which are not given. In studies of the effect of a hedge on air flow, Rider (1952) used cup-anemometers of similar type to those described by Sheppard (1940) (see Part Two, Chap. 7). Electric contact cup-anemometers have been employed by Woelfle (1939) in conjunction with counters and graphical recorders, power being supplied from accumulators.

For the determination of wind velocities in the vicinity of shelterbelts, Nøkkentved (1938, 1940) and Jensen (1954) employed pressure-plate or swinging-disc anemometers, which have been described in detail by the latter. The principle of this instrument is that a flat plate, suspended freely, becomes deflected by a stream of air to such an angle that the restoring torque due to the weight of the plate is equal to the air torque. In practice, a series of 20 or 25 readings of angular deflection were taken as rapidly as possible by the Danish workers and the mean recorded. By means of calibration in a wind-tunnel against a pitot-static tube the angular deflection may be converted to wind velocity and Jensen (1954) claims a 2 per cent accuracy for this instrument.

For the measurement of wind velocities and directions over protracted periods, Jensen (1954) used recording apparatus which he describes in detail. This apparatus consisted of a pressure-tube mounted on a direction vane and producing an anemograph record. In velocity studies near the ground Jensen also employed a multiple pitot-static tube with a multi-tube manometer, the readings being recorded by means of a revolving arrangement of a "Leica" camera.

Direction recorders have been used by Nägeli (1943-53) and van der Linde and Woudenberg (1951) to obtain continuous records of wind direction in the open, i.e. beyond the zone of influence of the shelterbelt under observation. Nägeli (1953a) records also the use of small direction-vanes in the study of air flow within the zone of shelter of artificial windbreaks. The Danish swinging-disc anemometer also included a small vane mounted above the pendulum.

(ii) Temperature Studies

Simple thermometers were employed by Bates (1911) for the measurement of temperatures within sheltered areas. Ordinary dry-bulb and minimum thermometers have been used by Nägeli (1943) and, more recently, minimum thermometers of the latest Swiss series, with a double bulb for greater sensitivity and an enlarged scale reading from -20°C to 20°C. Six's thermometers were used chiefly by van der Linde and Woudenberg (1951), the thermometers being exposed in white painted boxes made of eternite to minimise errors due to radiation; in later periods of observation thermographs were placed in standard meteorological screens.

Besides ordinary thermometers, Jensen (1954) used thermistors coupled with a Wheatstone bridge, up to 10 thermistors being used with the one bridge by means of a change-over switch.

Measurements of soil temperature have generally been made with soil thermometers of standard meteorological pattern or electric-resistance thermometers.

(iii) Humidity Studies

Various psychrometers or hygrometers have been been used for the determination of atmospheric humidity and dew-point, the "Assmann" psychrometer most commonly. Jensen (1954) has suggested the unsuitability of such instruments on account of the ventilation of the wet bulb causing excessive disturbance at the point of measurement. He used a dew-point indicator, designed by Weis-Fogh, consisting of a small glass tube with two platinum electrodes melted into its outer surface, a little ether being poured into the tube and allowed to evaporate. The apparatus was provided with a thermistor for determining the temperature of the bulb.

(iv) Evaporation Studies

Previous research workers in this field have employed evaporimeters, usually of the Piche or Livingstone types, as well as free-water surfaces. Bates (1911) used a circular sheet of filter paper resting on a thin glass plate, the paper being continually moistened by a supply of water fed on to the centre of the paper. The apparatus was exposed to sunlight and the circulation of air above the paper kept perfectly free so that it responded rapidly to changes both in temperature and wind velocity. Nägeli (1943) mentions the use of sensitive atmometers of his own design; these consisted of glass thistle funnels, 2 cm in diameter at the mouth, extending below into open tubes about 40 cm in length and 0.36 cm in diameter, with a capacity of 3.6 ml, the stems being graduated to read to 0.02 ml. When in use they were filled to the polished edge of the funnel with distilled water and covered with a flatground disc of unglazed porcelain, 3.5 cm in diameter and 0.5 cm thick, the porous disc acting as an evaporating surface. For field use these instruments have proved accurate to ± 2 per cent.

Evaporation studies from free-water surfaces have been made with shallow dishes (Warren 1941, Nägeli 1943). In all these studies absolute measures were not intended or required.

(v) Soil Moisture Studies

Few research papers give details of methods used for the measurement of soil moisture in the vicinity of shelterbelts. Jensen (1954) used a tensiometer of the Richards' type, which is based on the vapour pressure in the soil. A simple method for the comparative estimation of soil moisture in ecological studies has been evolved by Dimbleby (1954) and is described later.

B. EXPERIMENTAL METHODS

(i) Wind Studies

In the investigation of wind conditions within the vicinity of shelterbelts, some of the most detailed observations have been carried out with the use of latticed or solid artificial windbreaks. Bates (1924) used lath screens composed of 6-in. boards with 12-in. spaces in the lower half (representing the trunk space) and with 3-in. spaces in the upper half (representing the crown space), thus giving an overall average penetrability of 50%. Nøkkentved (1938, 1940) employed horizontal lath screens, 3.5 m high, with a penetrability of 38% (i.e. with 38% of the frontal surface area open). Jensen (1950, 1954) records the use of similar screens, 2.5 m high, with two degrees of penetrability, 45% and 71%. In Switzerland, Nägeli (1953a) constructed screens 2.2 m in height, using bamboo canes arranged vertically; the two screens had degrees of penetrability to the wind of 45-55% and 15-20% respectively. Studies have also been made with windbreaks composed of model trees, 1.5 and 3 m in height (Iizuka 1952).

In the majority of investigations of wind velocity, both with artificial windbreaks and natural shelterbelts, anemometers have been dispersed along a measurement line perpendicular to the sheltering obstacle or at other points within the zone of influence of the barrier on the windward and leeward sides. The velocity values recorded at these points have been related to the velocity measured during the same time interval at a "control" station situated beyond the influence of the windbreak or other obstruction and at the same height of measurement, the latter value being commonly expressed as the "free-wind velocity" or "open-ground velocity". The comparative results obtained are generally expressed as percentages of the free-wind velocity but Jensen (1954) uses the term "shelter effect", which may be defined as the ratio of the effective velocity reduction to the free-wind velocity.

Excepting the studies made with screens, where measurements have frequently been carried out at more than one measurement height, the standard height of measurement used in field observations by different research teams has varied within narrow limits only. Bates (1911, 1924) conducted all measurements at 4 ft. above ground, Danish workers at 1.5 m (Nøkkentved 1938, 1940; Jensen 1954), Gorshenin (1946) at 1 m and Nägeli (1943, 1946, 1953b) at 1.4 m. Nägeli explains that this height has been proved experimentally to be above the zone of maximum variation in wind pattern and velocity due to the ground surface; where measurements have been made, however, above long grass and agricultural crops, the instruments have been raised to maintain an effective height of 1.4 m. Woelfle (1939) conducted his wind studies with anemometers at 70 cm above ground, although, on the basis of wind profile studies (Paeschke 1937), this height would appear to be too close to the ground surface for general use.

In experiments with artificial screens, Nøkkentved (1938, 1940) recorded observations at 0.6 m and 1.5 m above ground and Nägeli (1953a) at elevations of 0.55, 1.1, 2.2, 3.3, 4.4, 5.5, 6.6, 7.7 and 8.8 m, i.e. from ¼ to 4 times the height of the screens.

Using the pendulum-type, pressure-plate anemometers, Nøkkentved (1938, 1940) employed one observer for each measurement station, one reading being taken every 5 seconds in a space of 2 minutes, giving 24 readings of which the mean was taken. In the investigation of wind conditions across Jutland (Jensen 1954), measurements were made every 20 minutes throughout the whole day, each measurement consisting of the average of 20 individual readings taken as rapidly as possible. Where counter-type anemometers have been employed, the velocities observed have been means taken over prescribed periods. Gorshenin (1946) records the use of 70 Fuess anemometers, which could be switched on and off simultaneously; whether this was achieved by individual manual operation or other technical means is not clear. Readings were obtained in exposures of 20 minutes duration. In his early shelterbelt studies, Nägeli (1943) employed four observers for nine anemometers dispersed along a measurement line; when the distance between instruments made it possible, readings were taken at 15-minute intervals or, at worst, every half-hour and wind direction was recorded every 3 to 5 minutes. In later research (Nägeli 1946), a similar procedure was adopted, 18 anemometers being used along each measurement line. He records that all measurements were eliminated which showed too marked a deviation of the wind direction from the direction of the measurement line.

(ii) Temperature Studies

Temperature measurements have generally been carried out at the same points used for the investigation of wind velocity, where such measurements have been supplementary to wind studies. Where temperature studies predominated, e.g. van der Linde and Woudenberg (1951), various heights of measurement have been used, the measurement line being normal to the shelterbelt, and observations have usually been conducted over longer periods. The Dutch observers recorded temperatures at 10, 25, 50 and 150 cm above ground and where thermographs were used in screens the latter were raised 40 cm above ground and not to the standard height for meteorological stations.

During experiments on microclimate and crop yields in sheltered areas, Jensen (1954) measured the air temperature 3 times daily and calculated means for 10-day periods. Soil temperatures were measured at 20 cm below ground once daily. During a few periods, occasional measurements were made of air and soil temperatures, using thermistors, observations being made at several points simultaneously.

(iii) Humidity Studies

Experimental methods of determining the absolute and relative humidity of the air near windbreaks have varied according to the instruments used but generally have consisted of instantaneous measurements made at any one point and not means over a given period. In consequence, the possible error in comparative assessment of humidity relationships has been fairly high. Where an observation made by means of an Assmann psychrometer consisted of 10 pairs of readings (van der Linde and Woudenberg 1951), a considerable time elapsed between the first and last observations along a measurement line. Therefore, during periods liable to rather rapid fluctuations, such as morning and evening, no humidity observations could be made. Similarly, Jensen (1954) recorded measurements of humidity under certain special climatic conditions only.

Generally, humidity studies have been carried out in conjunction with temperature observations and at the same positions.

(iv) Evaporation Studies

Measurements of evaporation have been made usually along a measurement line normal to the shelterbelt, the evaporimeters being exposed for a certain period, generally of half an hour or longer, and the amounts of water evaporated during this period related to the amount evaporated during the same time from an evaporimeter exposed at the same height above ground outside the influence of the shelterbelt. Evaporation has rarely been assessed by means of instantaneous readings of saturation deficit.

(v) Soil Moisture Studies

Jensen (1954) determined soil moisture content during the first year of experiments by taking samples of soil with an auger once or twice weekly and after precipitation, the samples being subjected to desiccation analyses. During the last two years, tensiometers were used daily; measurements were presumably carried out successively at various points.

Section 2. Laboratory Investigations

A. INSTRUMENTATION

(i) Wind Studies

In general, laboratory investigations in this field have been carried out by means of model tests in wind-tunnels but, in addition, studies of the pattern of fluid flow over model windbreaks in a water-tunnel have been recorded photographically (Blenk 1952). Wind-tunnel observations have been based on horizontal velocity ratios to windward and/or leeward of model windbreaks and on the effect on erosion and snow-drift patterns.

Velocity values obtained in wind-tunnel experiments are based on the fact that, in fluid dynamics theory,

$$p=\tfrac{1}{2}\rho v^2$$

where p=pressure, ρ=density of the fluid and v=velocity of the fluid. A body immersed in a moving fluid is acted upon by a static pressure, which acts equally in all directions when the fluid is stationary and persists, although its magnitude may be changed, when the fluid is set in uniform, unaccelerated motion, and also by an additional pressure arising from the impact of the moving stream. In practice, therefore, an open-ended tube pointing upstream and with the other end connected to a simple pressure gauge will register the sum of the impact and static pressures, commonly called the "total head". In order to obtain the "velocity head", the pressure which is a function of the motion of the stream only, the static pressure must be deducted from the total head reading:

$$p_1-p_0=\tfrac{1}{2}\rho v^2$$

This differential pressure, (p_1-p_0), is commonly measured by a combined pitot-static tube, consisting of a double tube whereby the total head and static pressures are measured at the same point in the stream; when the two parts of the tube are connected to the two arms of a differential manometer, the pressure due to the velocity head is registered automatically. Owing to the fact that, within wide limits, the impact pressure measured by a facing tube is unaffected by the shape and size of the tube, various types of pitot and pitot-static tubes are used in practice. In view of the small scale frequently employed in wind-tunnel models and the difficulty of constructing very small pitot-static tubes, total head tubes are often used, the static pressure being measured at some other convenient point within the test section of the tunnel; where the static pressure is not measured in the same cross-section of the tunnel as the total head, the necessary correction is usually determined experimentally.

In the study of model windbreaks, types of wind-tunnel and pressure-measuring instruments have varied somewhat. Finney (Pugh 1950), investigating snow fences, used a small wind-tunnel with test section 2 ft square and 10 ft long. It included a 3-ft propellor, powered by a 5-h.p. D.C. motor, capable of producing velocities up to 45 mi/hr. A small pitot-tube was employed to trace out the eddy areas.

The Danish workers, Nøkkentved (1938, 1940) and Jensen (1950, 1954), used a wind-tunnel of the open-circulation (N.P.L.) type, with a test section 60 cm (=2 ft) square and approximately 5 m long and a 30-h.p. propellor motor capable of a maximum velocity of 32 m/sec. In the latest studies, velocities were determined by means of a Prandtl pitot-static tube, with horizontal branch 9 cm long, but for more precise measurements near the 5-cm high models a smaller pitot-static tube was constructed. This consisted of two branches of tubing of external diameter 1 mm, the longer horizontal branch (static) being 1.2 cm in length, closed at the end but provided with two lateral holes, 0.09 mm in diameter, adjacent to the open end of the shorter (dynamic) branch. This instrument was used in conjunction with a holder, allowing measurements to be made at any point in the vertical or horizontal symmetrical planes of the wind-tunnel within an accuracy of 0.01 cm, and a Fuess inclined-tube manometer, the latter verified against a vertical Prandtl manometer with an accuracy of 0.005 cm spirit column. By means of a Fuess change-over mechanism, the manometer could conveniently be connected with several measurement points successively. "Cylinder meters" were used for the determination of the direction of flow within horizontal and vertical planes. Detailed descriptions of the complete apparatus have been published (Jensen 1954).

The tunnel used by Woodruff and Zingg (1952, 1953) had a test section of at least 12 ft in length, beginning at a point 40 ft down-wind from the fan. A vertical arrangement of four pitot tubes, which could be lowered from the roof of the tunnel on a staff gauge equipped with a vernier scale for accurate and rapid vertical movement, was employed, pressures being recorded on an Ellison manometer. The tunnel roof was so constructed to allow horizontal movement of the pitot tubes through the entire working section. Aluminium powder was introduced into the air stream and strongly illuminated for sketching streamlines of flow.

In Germany, Blenk (1952, 1953) used a tunnel with a test section 2.5 m long and 0.60 m wide. Pressure measurements were made by means of a pitot tube, 4 mm in diameter, on an adjustable mounting, coupled to a Prandtl manometer.

B. EXPERIMENTAL METHODS

(i) Wind Studies

Model snow fences, used by Finney (Pugh 1950), comprised horizontal- and vertical-slat and solid types on a scale of 1 in. to 2 ft, representing a height range in nature of 2-10 ft, and were erected across the whole width of the tunnel. His investigations mainly concerned the pattern of snow drifting behind the models, as described later.

The models used by Nøkkentved (1938, 1940) and Jensen (1950, 1954) were 5 cm in height, consisting of various structures and degrees of penetrability. Nøkkentved records measurements taken at $\frac{1}{6}$th of the height of the screens, the results being expressed as percentages of an undisturbed velocity at the same height of 10 m/sec. The penetrable screens had perforations 4 mm in diameter with the exception of one experiment with natural spruce twigs. In the latter case 1 or 2 rows of twigs were used, with a spacing between rows of 1 cm and within the rows of 1.5 cm; the twigs were clipped down to 5 cm in height. Measurements were continued to a leeward distance of 57 times the height of the models along a centre line. In the course of studies of systems of screens (Nøkkentved 1940), the heights of measurement were 0.16, 0.5, 1.1 and 1.5 times the height of the models. Jensen (1954) carried out re-measurements to leeward of Nøkkentved's screen types which were supplemented with a few of different structure, such as screens composed of horizontal, cylindrical rods, vertical palings and rectangular lattice. Measurements are recorded down to 0.1h but usually only to 0.2h (1 cm) above the tunnel floor. The values obtained are expressed as relative shelter effect, i.e. the reduction in velocity due to the presence of the screen as a percentage of the velocity of the unobstructed air current at the same place of measurement. Down-wind measurements were taken to 70 times the model height. In Germany, Blenk used 5 cm models (1952) and 3 cm models (1953); in both cases, the undisturbed velocity in the tunnel was 40 m/sec, the measurement line extended 30h to windward and 30h to leeward of the models and velocities were recorded at heights above the tunnel floor of $\frac{1}{3}$h and one-sixth times the height of the model. His results are expressed as a ratio of the velocity measured at a point with the model in position to the velocity measured at the same point in a clear tunnel.

The model shelterbelts studied by Woodruff and Zingg (1953) were fabricated from cedar twigs placed in short lengths of $\frac{1}{4}$-in. aluminium tubing, mounted in a plywood base. The scale used was 1 in. to 5 ft so that the maximum height in the models was 6 in., the spacing between trees 1 in. and between rows 2 in., resulting in 36 trees/shrubs per row. Horizontal velocity measurements were recorded at 12 heights and 23 locations in the air flow, a constant wind velocity of 31 mi/hr being maintained at an elevation of 2h above the trees. Velocity profiles were obtained by plotting the dimensionless ratios z/h and U_t/U_c, where

- z = elevation above datum (0.1 h to 3.1 h)
- h = height of tallest tree in the models
- U_t = velocity in tunnel with shelterbelt in position
- U_c = velocity at corresponding point in clear tunnel

The measurement line extended 2h windward and 23h leeward of the models.

In addition to velocity measurements, Woodruff and Zingg (1952, 1953) studied the shelter effect at the ground by means of erosion or shear patterns, based on the concept that the velocity ratio u/u_o is related to levels of shear as follows:

$$\frac{u}{u_o} = \sqrt{\frac{T}{T_o}}$$

where u_o is the threshold velocity for a given erodible material in a clear tunnel, u is a velocity of known magnitude greater than the threshold, also measured in a clear tunnel, T_o is the threshold shear and T is a shear of known magnitude greater than the threshold. Dune sand of the size 0.30-0.42 mm was used to delineate the area of protection to leeward of the model windbreaks. Four levels of wind, each yielding values of u/u_o greater than unity, were passed over the models and sand and the boundary of sand remaining at the end of each test denoted the approximate location at which the barrier reduced the shear at bed level to the threshold value. This is the equivalent of reducing the ratio u/u_o to unity at the same point, this reduction being known as the effective velocity reduction, which, expressed as a percentage is:

$$\text{Effective velocity reduction} = \frac{100\left(\frac{u}{u_o} - 1\right)}{\frac{u}{u_o}} = 100\left(1 - \frac{u}{u_o}\right)$$

To investigate the boundary layer over a wood, Jensen (1954) mounted corrugated paper on a flat plate 1.2 cm thick, the corrugations being 3 mm high and 8.8 mm long. These models extended over the entire width of the tunnel and their extent in the direction of the wind varied from 30 to 310 cm; considering the overall height as 1.5 cm, the models represented widths of 20 to 205h. Down-wind measurements were taken to 70h. The model of the wide woodland strip, used by Blenk (1952), appears to have consisted of parallel fences with no continuous upper edge. Blenk (1952) considered also the effect of topography on the siting of shelterbelts by introducing undulations in the form of a double sine-curve along the floor of the tunnel.

Generally, wind-tunnel experiments on this subject have followed a fairly similar pattern throughout.

(ii) Evaporation Studies

Blenk (1952) investigated evaporation from damp soil in the laboratory, air from a jet 60 cm above ground being passed over three cups of soil sunk one behind the other in a slab level with the ground. The rate of evaporation was measured as the loss in weight after a period of 50 min. Fences were then introduced in front of the cups and the relative reduction in evaporation rate observed.

(iii) Transpiration Studies

Samples of clover and grass were cut as turves, 20 cm in depth, placed in boxes of zinc sheeting of the same dimensions and subjected to detailed laboratory study over periods of several days by Jensen (1954). The plants were illuminated artificially for 12-16 hrs daily and exposed periodically or continuously to wind in a wind-tunnel at various speeds. The boxes were weighed periodically to determine loss through evaporation and at the end of each experiment the leaf area of each sample was obtained by direct measurement.

(iv) Snow-drifting Studies

As artificial snow for wind-tunnel experiments, Finney (Pugh 1950) used flaked mica and very fine sawdust. Velocities up to 25 mi/hr were obtained in the tunnel. The drift patterns were observed after the tunnel had been running for a certain period. The tunnel was lined with coarse sand-paper to resemble the ground more closely. Similarly, Nøkkentved (Pugh 1950) employed sawdust and covered the tunnel floor with coarse paper, the tunnel speed varying between 13 and 34 mi/hr. Becker (Pugh 1950) used peat dust and gypsum separately as artificial snow. In all these studies different fence types were introduced into the stream and their effect in terms of drift length and depth noted.

Chapter 7

POSSIBLE DEVELOPMENT OF EXPERIMENTAL METHODS AND INSTRUMENTATION FOR FUTURE RESEARCH

Section 1. Field Investigations

IN CONSIDERING possible developments of experimental technique and instrumentation for field investigations of microclimates in the vicinity of shelterbelts, it is evident that wind velocity and direction, as the controlling factors with regard to further climatic changes, must be subjected to the closest investigation. It has been demonstrated by previous research workers that the basic approach to the investigation of any one of the physical features of microclimates, whether wind velocity and direction, atmospheric temperature and humidity, evaporation, transpiration or soil moisture and temperature, lies essentially in simultaneous measurement of a particular climatic factor at various points within a prescribed area and the relation of these observations to a standard value for this factor recorded at the same time. In regions of varying topography, where periods during which the wind exhibits reasonably constant direction and velocity, suitable for field investigations, are strictly limited, the difficulties encountered in such studies are readily apparent. For any short-term observations the necessary equipment must be easily portable and capable of erection and observation with the minimum of time wastage in the field. Assistance in field-work is limited generally both economically and in availability. These considerations and restrictions dictate to a very large extent the suitability or otherwise of experimental methods and instruments for research in nature.

(i) Wind Conditions

For the study of wind velocity near the ground, the range of anemometers suitable is restricted by theoretical considerations. Sensitivity to low wind speeds, the maximum freedom from over-estimation in fluctuating winds and capability of responding to changes of direction, at least within a horizontal plane, especially since areas of disturbed flow are inevitable in the vicinity of any obstacle, are essential requirements. These conditions eliminate several available instruments.

In the range of pressure anemometers, none of those instruments involving a flow of air through the anemometer, e.g. the plate orifice, nozzle and venturi tube, is generally used in outdoor practice. Where no air flow through the instrument is incurred, as in the pressure-tube anemometers and pitot tubes, the use of the former type is curtailed by the high cost of manufacture and large size of the complete assembly. It is noted that instruments of this type have been constructed and used for graphical recording of wind velocity and direction in Denmark (Jensen 1954) but only where requirements necessitated the use of recording equipment over periods of several days. Pitot tubes have also been used in field investigations in Denmark but, owing to the error introduced when the tubes are not maintained in a direction parallel to and facing the wind stream, their use under natural climatic conditions must be considered impracticable.

Of the mechanical anemometers, each of the three main types, cup, swinging plate and vane anemometers, has been used frequently in microclimatic investigations, the cup anemometer most extensively. One of the simplest patterns of cup anemometer is the standard Meteorological Office Cup-Counter Anemometer Mk. II (Plate 1). Though not normally intended for use near the ground, it has been found to be a convenient instrument for semi-permanent installation in exposed situations at 1.5 m above short grass. This anemometer depends in principle on the rotation of a system of three cups mounted on a vertical spindle. The rate of rotation of the cups is directly proportional to the speed of the wind to a sufficiently close approximation. The "factor", or ratio of the distance travelled by the wind to the distance travelled by the centre of any one cup, which in this instrument is conical, is 2.98. The spindle operates a counter mechanism registering the run of wind in miles to 0.01 mi; the indicated wind speed is within 1 mi/hr of the true wind speed throughout the range of the instrument and no corrections are necessary.

Probably the most suitable cup anemometer available is the Sensitive Type IV anemometer, designed by Sheppard (1940) and subsequently modified and manufactured by Casella & Co., London (Plate 2). Of extremely light construction, fitted with a 3-cup rotor of radius 3 in., the conical cups being 2 in. in diameter, this instrument is intended for the accurate measurement of low wind speeds yet can stand exposure to winds of 88 ft/sec. The spindle supporting the cup rotor activates a lightly geared counting mechanism and the combined frictional torque of the assembly does not exceed 20 dyne/cm, which gives a stopping speed of 0.3 ft/sec. With a linear calibration and satisfactory behaviour in fluctuating winds, this anemometer appears most suited for microclimatic reaearch and investigations of atmospheric turbulence.

Investigations into the over-estimation of mean wind speed in a variable wind for the Sheppard anemometer and Meteorological Office patterns of the 3-cup type reveal that conical cups over-estimate to a much smaller extent than hemispherical cups and are to be preferred therefore when unsteady (i.e. natural) winds are being measured (Scrase and Sheppard 1944).

The Sensitive Type IV anemometer is available commercially with a micro-electric contact mechanism, operating at 6 volts, instead of the counter. Two contacts are made for every three revolutions of the cups; with a counter of the P.O. message register type up to 9999 counts may be recorded. This system, due to Deacon (1948) and subsequently modified by Crawford (1951), enables the counter to be situated remote from the anemometer. By this means, anemometers may be erected some distance above ground, the counters remaining at ground level, thus rendering the instrument ideally practical for forest meteorological studies.

Pressure- or swinging-plate anemometers, depending on the deflection of a pendulous plate or disc by the wind, are now rarely used. The particular design considered here, the Danish swinging-disc anemometer, has been used with some success in that country (Nøkkentved 1938, 1940; Jensen 1950, 1954). Consisting of a wire ring covered with a gauze mesh, with a pointer moving against a graduated scale, the instrument has been calibrated against a pitot-tube in a wind-tunnel and results of field measurements and has demonstrated its potentialities. It is simple in design and construction and when linear to the wind stream mechanical error is minimised. On the other hand, the difficulties of observation, owing to the fact that a mean must be taken of several rapid readings of the angular deflection of the disc, thus necessitating continual observation of each instrument, render its use in practice uneconomic. Also, the error introduced when the wind stream is not normal to the disc, a feature inevitable in natural winds, particularly in the vicinity of obstacles, must cause a comparatively low degree of accuracy in the investigation of wind conditions near shelterbelts when the flow pattern is considerably disturbed.

The air meter or vane anemometer (Plate 2), available in several similar designs, consists usually of eight flat vanes radiating from a common spindle. When the axis of the spindle is set along the direction of flow of the wind, the "windmill" rotates at a rate proportional to the wind velocity. In practice, the instrument can be yawed through about 20° before an error of 1 per cent is incurred on the indicated speed. In a fluctuating wind, a vane anemometer over-estimates the average speed and this error is proportional to the square of the amplitude of the fluctuations; where the velocity extremes are less than 15 per cent on either side of the mean the error should not appreciably exceed 1 per cent but, for a 50 per cent fluctuation, the error may be as much as 12½ per cent (Ower 1949). In field studies of shelterbelts it has been found that, within the area of disturbed flow caused by the belts, the vane rotates alternately clockwise and anti-clockwise according to pulsations in the eddy area. These limitations restrict the practical use of this instrument.

Anemometers employing the relationship between the rate of heat loss from a heated body and the speed of flow of the fluid in which the instrument is immersed, have a restricted use in field investigations of microclimate. Geiger (1950) considers the construction of the Albrecht electrical hot-wise anemometer to be of great significance in microclimatology owing to its suitable design for meteorological field work. This anemometer has been used to investigate the penetration of the wind into a dense stand of spruce (Woelfle 1942). The principle of hot-wire anemometers is that a pure metal wire, when heated in a simple electrical circuit and exposed to an air current, is cooled by the air. If the wire is maintained at a constant temperature and, consequently, at a constant resistance, the current varies with the velocity of the air stream; the current can be measured with an ammeter or voltmeter of high resistance. An alternative method is for the current to be kept constant so that the wire temperature and resistance vary according to the wind velocity. In practice, many instruments of this type possess an unstable calibration; the Simmons Shielded Hot-wire Anemometer is considered to have a more permanent calibration than most types (Ower 1949).

The Hastings Portable Air Meter (Hastings Instrument Co., Inc., Hampton, Virginia, U.S.A.) is designed for measurement of air velocity and static pressure by means of a sensitive thermopile and is particularly free of errors due to temperature variations (-20° to 250°F); radiation, lead resistance and humidity effects are negligible. The noble metal thermopile contains six thermo-couples on coin-silver mountings fitted in a directional probe (Plate 3). The hot junctions of the thermopile are heated by passing alternating current through them. The cold junctions are prevented from becoming heated by lowering their resistance and by increasing the heat conductivity away from these junctions. A DC current is therefore generated between the hot and cold junctions of the thermopile. The AC heating power is separated from the DC voltage generated by the thermopile by the use of a half-bridge circuit. The DC voltage is generated across points of equal AC potential, thus eliminating effects of the AC heating current on the DC voltage output. The flow of air by the thermopile tends to bring the hot and cold junctions to the same temperature thus reducing the output of the thermopile. The voltage output is therefore a measure of the speed of the air flowing by the thermopile. An indicator is operated from the thermal difference voltage generated by the thermopile. This instrument has two velocity ranges, 10-750 ft/min and 750-5500 ft/min respectively and is equipped with three 1½-volt batteries.

In field tests of this instrument, it has been found that the probe is too sensitive for instantaneous velocity measurements in the open, owing to the rapid and wide fluctuations of the indicator. For measurement of the penetration of light winds inside dense stands, where the use of a mechanical anemometer is not feasible or possible, and also for measurements within a low plant cover, such as amongst grass and cereal crops, the Hastings Meter would appear to be the most suitable anemometer available.

Another instrument which relies upon a rate of cooling as a measure of velocity is the Kata thermometer, designed by Hill (1916, 1922) for research on the effect of atmospheric conditions on health and industrial efficiency. Essentially an alcohol thermometer of special type (Plate 84), the bulb is warmed until the spirit rises in the tube. When exposed to the air stream, the time taken for the column to fall between two limits of the scale, in this case 100° and 95°F, is related to the cooling power of the wind and, hence, is a measure of its velocity. The velocity is obtained by means of the formula

$$H=(a+b\sqrt{V})\theta$$

where a and b are constants, θ is the mean excess temperature of the Kata thermometer over that of the surrounding air, and H is the total heat lost in cooling from 100° to 95°F, divided by the area of the cooling surface and by the cooling time. The use of this instrument as an anemometer is restricted mainly to the measurement of the speed of moving air currents in the study of ventilation problems in rooms and enclosed spaces. It has the advantage that it is largely non-directional, giving values of the resultant air speed past the bulb practically independent of the direction of flow. Disadvantages are the length of time necessary to take readings and the comparatively low accuracy. In field tests, the latter has been found to be very marked, thus reducing its utility, although, as a "comfort meter", to study the effect of atmospheric conditions on animals in relation to the application of shelter where necessary, it would appear to show great promise.

To summarise, for the study of wind conditions in the vicinity of shelterbelts and in general microclimatic studies of wind velocity between 1 and 2 m above ground, the Sensitive Type IV anemometer, either of the counter or micro-electric contact type, would appear to be most suitable instrument available in the United Kingdom. In the investigation of wind conditions at higher elevations above ground, such as above a forest canopy, the micro-electric contact version of this anemometer would be most practicable.

In considering the practical application of the most suitable of the available instruments to field investigations of wind conditions in the vicinity of shelterbelts and in relation to their siting on exposed ground, it is evident that, ideally, 20 or more anemometers would be required to obtain comparative measurements. In the study of individual belts, these instruments would require to be dispersed along a measurement line commencing 10 shelterbelt-heights to windward and extending 30 heights to leeward in order to cover the maximum sheltered zone to be expected. Assuming a maximum shelterbelt height, either actual or potential, of 60 ft, a measurement line of 800 yd would have to be allowed for. In the study of wind velocities on bare hillsides and over ridges, with regard to site selection for belts, a considerably longer range of measurement might be necessary. In order to obtain simultaneous measurements of wind speed at several points throughout this range, unless each instrument were to be individually manned, some device by which a whole battery of anemometers could be switched on and off simultaneously, or, alternatively, have their reading recorded, would appear essential.

Consideration has been given to the possibility of developing an electro-mechanical apparatus on the solenoid principle to engage the on-off levers on anemometers such as the Sensitive Type IV counter-type instrument. However, owing to the distance through which the average on-off lever has to be moved and the dissipation of the necessarily low current through the length of the connecting wire, such apparatus is unlikely to be satisfactory. A more practical arrangement might be the use of the micro-electric contact version of the Sensitive Type IV anemometer, which has become available commercially more recently, with the individual counters assembled at one central point. For short-term observations extending over not more than one or two days at a time, however, the use of long distances of electric cable, especially with the difficult ground conditions and presence of field crops or grazing animals frequently to be encountered in experimental areas, is hardly practicable.

It is possible that electronic apparatus could be developed for this purpose but such equipment is expensive to construct and maintain and, it may be assumed, would require skilled attention in the field from time to time. The possibility has been considered also of employing a time-operated camera recorder to record the reading of an instrument at given time intervals, in order to obviate the necessity of employing one observer per instrument. Tests have been carried out using a clock equipped with a light electric contact operating every five minutes. The contact activated a 24-volt Camera Recorder G.S., ex Air Ministry surplus stores, equipped with approximately 15 ft of 16 mm film. Owing to the time taken for the electric contact in the clock to break, during which interval the camera recorded on the average two frames per second, some means of controlling the number of photographs taken was essential. A thermal delay circuit was therefore introduced and it was found that, by varying the resistance of this circuit according to temperature conditions, the camera could be controlled so as to take one or at the most two successive photographs for each closure of the main circuit, irrespective of the time taken for the clock contacts to reopen the circuit. In practice, however, the use of this recorder with the counter-type of anemometer is not altogether suitable since the camera requires to be too close to the cup assembly, thereby disturbing the air flow in this region, and also atmospheric conditions are apt to foul the dial of the anemometer or the lens of the camera and obscure the reading on the photograph. However, using the electric contact version of the Sensitive Type IV anemometer, where the counter can be remote from the actual instrument, it would be possible to enclose counter and camera recorder in a weather-proof case with interior illumination, an arrangement which has obvious practical possibilities in microclimatology.

Generally, graphically recording anemometers, providing a continuous record of wind speed, are too bulky for microclimatological studies of wind conditions, especially for short-term observations.

In order to obtain a standard value of wind velocity for comparison with values recorded at the various points throughout the measurement area, it is necessary to operate a "control" station at a freely-exposed situation in the open. In practice, a point at least 10 shelterbelt-heights to windward of the belt under observation will register the "free wind" or "open ground wind" velocity, provided it is beyond the range of other sheltering obstacles.

Where it is not possible to employ a system, whereby a whole series of anemometers can be switched on and off simultaneously, it might be considered possible to operate a "control" station, producing some form of continuous or intermittent record of wind velocity over a given period at that point, using an expanded time-scale to facilitate analysis of the results, and then to take either instantaneous or short-interval readings at the various measurement points successively, relating these to the continuous record obtained at the control station. Certain disadvantages would be involved, notably that the readings would not be simultaneous at all places of observation and instantaneous or short-interval values of wind speed are more difficult to compare than averages over a longer period. On the other hand, only one instrument would be required, excluding the control anemometer, thereby minimising calibration errors. Where the order of magnitude of the microclimate under observation precludes the use of a cup-anemometer and suggests the use of a hot-wire instrument, a procedure along these lines would appear to be indicated.

In the comparative study of natural winds, it is more satisfactory to employ totalising instruments, yielding an aggregate distance run of wind, rather than to rely on instantaneous velocity measurements, since fluctuations of velocity will not be simultaneous at observation posts more than a short distance apart. A more practical arrangement therefore, and the one generally adopted, is to employ a series of simple counter-type anemometers and to distribute as many observers as possible along the measurement line. The advantages of this method, used successfully by Nägeli (1943-53) among others, are that the equipment is easily erected for observation, one standard type of instrument is used throughout so that the anemometers are interchangeable; when one or more instrument proves faulty the rest of the series is not affected and, after preliminary observations, the instruments can be re-distributed or added to, especially where certain points in the measurement area obviously require more detailed study. Unless one observer is available per instrument, it is inevitable that an error will be introduced through the readings not being simultaneous at all points. Its magnitude must depend on the number of assistants available, the distance between anemometers and, thus, the delay between successive readings. The proportionate error can be minimised by increasing the exposure periods to, say, half an hour or one hour. It is obviously desirable for all intended observation points within the experimental area to be equipped with instruments at the same time, since this procedure allows several readings to be observed at each point. It is possible then to reject those measurements for periods when the wind direction showed marked deviation from the average or other atmospheric conditions proved unsuitable and to take a mean of the values for the favourable periods. This method also allows a preliminary appraisal of the results during the course of the investigations. Its practicability, however, will be limited by the supply of instruments; with a small number of anemometers the whole of the measurement area cannot be studied simultaneously and fewer readings can be taken at each observation point. In this case, careful attention to changes in wind direction is essential. A wind direction recorder or, at least, a light wind-vane which is observed frequently would seem necessary at the control station.

With regard to the exposure of anemometers in general field investigations in connexion with shelterbelts, a standard height of measurement above ground is necessary. It is considered that a height of 1.5 m (approximately 5 ft), being above the zone of maximum variation in velocity due to the ground surface and corresponding very closely to the height laid down for the exposure of thermometers etc. at climatological stations, would be most convenient.

In laying out a measurement line in the vicinity of a shelterbelt, the normal practice is for the line to be perpendicular to the belt and measurements to be recorded at distances in multiples of shelterbelt height along this line. Where the wind direction is not normal to the belt, the effective distance of the measurement point from the belt is considered as that distance parallel with the wind direction and the appropriate correction is applied usually by a simple trigonometrical calculation according to the angle of incidence of the wind direction to the belt. In practice, corrections for small deviations in wind direction from the normal affect the results very slightly.

In areas where detailed investigation of microclimatic wind conditions is contemplated it is obviously an advantage to have simultaneous records of wind velocity and direction at the standard height of 10m (33 ft) used by meteorological stations, obtained either from nearby stations where possible or by means of a temporary anemometer fixed at this height above ground. In this way, the results of microclimatic research can be related to the general weather conditions and may have a more far-reaching practical application.

(ii) **Temperature Conditions**

The comprehensive study of temperature conditions implies long-term observation and occasional measurements undertaken in the vicinity of shelterbelts have yielded little information of practical value. Detailed study of temperature conditions in a sheltered area would necessitate observation throughout a whole year, or at least a growing season, at several points including a "control" station beyond the zone of protection afforded by the belt. For this purpose, thermographs together with maximum and minimum thermometers, all enclosed within some form of screen, would be suitable. In addition, grass minimum thermometers and apparatus for measuring soil temperatures would be desirable and, in order to assess the results of these observations within the general climatic pattern, associated studies of atmospheric humidity and radiation an advantage. It is apparent, therefore, that very detailed research on temperature conditions must be considered a major undertaking and any short-term observations an essentially incomplete representation. For practical purposes, a comprehensive scheme of such investigation must be restricted to a few shelterbelts in selected areas at the most; probably this could be achieved in association with research on agricultural crop yields in sheltered areas. In a comparative study of several shelterbelts on different types of soil, with varying plant cover in their adjacent areas and under widely fluctuating weather conditions, it is inevitable that temperature studies become limited, particularly when wind velocity and flow pattern are the chief objects of investigation.

Considering occasional measurements of atmospheric temperature to be carried out in conjunction with, and complementary to, studies of wind conditions, in a storm all microclimatic differences vanish and therefore windy and stormy days are generally unsuited to observations of microclimatic factors (Geiger 1950). This would appear to indicate that a few instantaneous measurements of temperature carried out at the same positions as wind velocity observations are not likely to be very reliable except in rare cases. It would seem, therefore, that temperature studies should be restricted to measurements with ordinary dry-bulb thermometers, simply screened against radiation effects, when suitable conditions permit. On radiation nights the effect of a shelterbelt could probably be studied by means of a series of sheathed grass minimum thermometers set up along a measurement line normal to the belt, although slight changes in ground cover must be expected to complicate the results.

Soil temperatures in short-term investigations would require to be measured with an electric resistance thermometer, readings being instantaneous; for longer periods standard meteorological earth thermometers would appear suitable.

(iii) **Humidity Conditions**

As with temperature observations, the occasional measurement of humidity relationships in microclimatology presents certain difficulties. Geiger (1950) refers to the manifold limitations in adapting the technique of atmospheric humidity measurement to the needs of microclimatic research: the usual hair hygrometers fail to work in the ground air layer because they are too large and psychrometers because they require circulating air, thereby introducing a disturbance of the microclimate. Jensen (1954) has objected to the use of whirling hygrometers and psychrometers in the field for the same reason; in the Danish investigations the Weis-Fogh apparatus for the determination of dew-point was therefore used, this instrument being based upon the vaporisation of ether. Geiger (1950) mentions also a method of humidity measurement depending upon the fact that, if dilute sulphuric acid is in contact with air whose vapour pressure is greater than the saturation pressure of the acid, the air will give up water to the acid until equilibrium is attained and vice versa. The apparatus consisted of small capillary tubes, 3 to 5 mm long, which were filled with sulphuric acid solutions of various concentrations, varying by steps corresponding to 5 per cent on the humidity scale. After 10 minutes it could be observed with a magnifying glass whether the liquid surface, which was just even with the end of the tube, had risen or fallen and from this the relative humidity could be determined, the temperature error being negligible.

Thermistor elements constructed in pairs as wet-and-dry-bulb resistance thermometers and calibrated over a range of wind speeds against an Assmann psychrometer, so that ventilation corrections could be made in deriving values of humidity, have been designed by Penman and Long (1949) for humidity measurement in potato crops. Their use has been described by Broadbent (1949, 1950).

In field studies the time lapse between successive instantaneous measurements of humidity restricts observations to periods when atmospheric conditions are more or less constant and fluctuations negligible, conditions which are comparatively rare. It would appear that for occasional observations during favourable periods atmospheric humidity should be determined by apparatus, as described above, which does not require circulation of air at the wet bulb. For measurements over longer periods a recording hygrograph, suitably screened, would probably be most efficient.

(iv) **Evaporation and Transpiration Conditions**

Probably the most useful form of observation, suitable as an efficiency index of a shelterbelt, is the study of a factor which embodies wind, temperature and atmospheric humidity conditions and their continual fluctuations, i.e. evaporation and transpiration. In the light of the considerable scientific and observational evidence it would appear that it is the desiccating or evaporative power of the wind which is critical for vegetation and, similarly, the cooling power or "exposure" factor which is detrimental to animal welfare, frequently with fatal consequences. Apart from the reduction of mechanical damage to plant life brought about by shelterbelts, it is the diminution of the evaporative power of the wind which largely constitutes "shelter".

Considerable research on evaporation potential and its relation to ecological problems has been undertaken in America (see, for example, Thornthwaite 1940, 1954; Thornthwaite et al. 1948-52; Thornthwaite and Holzman 1939, 1942) and at Rothamsted (Penman 1941a and b, 1951 etc.); these investigations have emphasized the importance of this factor, particularly in agriculture.

In the comparative study of shelterbelt influences, therefore, it would appear that a series of simple evaporimeters would supply the necessary qualitative data. Although the loss of water from evaporimeters or atmometers cannot be taken as the absolute quantitative measure of transpiration from the living plant or evaporation from moist soil, these instruments, in spite of their many defects, have the decided advantage of integrating the changes in the rate of evaporation during the intervals of time for which they are exposed (Maximov 1929) and are to be preferred to instantaneous measurements of saturation deficit, relative humidity or dew-point.

Several evaporimeters, such as those due to Livingstone, Pickering and Piche, are available commercially and have been used frequently in ecological and microclimatic studies. However, both the Livingstone and Pickering types are comparatively expensive and somewhat clumsy for temporary erection in the field. The disadvantage of the Piche type is that it must be clamped rigidly vertical to prevent displacement of the porous paper evaporating surface which is held by a clip at the bottom of the cylindrical tube containing the water. It is therefore a difficult instrument to use in a strong wind, movement of the tube causing occasional drips from the porous surface and, thus, over-estimation of the rate of evaporation. A simpler apparatus has been designed by Nägeli (1943) and used successfully in his later investigations in Switzerland. A similar version of this instrument, made to order in this country, consists of a glass thistle funnel, 3.5 cm in external diameter at the mouth, with ground and polished edge, extending into a 40 cm long stem of 3.5 mm bore, open at the bottom, and graduated in millimetres upwards (Plate 5) (Griffin & Tatlock, Edinburgh). The porous disc, 4.0 cm in diameter and flat-ground to a thickness of 5 mm, is manufactured from F-10 grade porcelain (Doulton & Co., London) with a measured maximum pore size of 7-10 microns approximately and an approximate rate of flow of water through a thickness of $\frac{3}{16}$ in. (0.48 cm) for a pressure drop of 1 lb/in.^{2} (51.7 mm mercury) of 150 pints/ft^2/hr (900 litres/m^2/hr).

The measure of evaporation rate is the distance the column of water moves up the stem of the funnel in a prescribed period as water is evaporated from the porous surface, which makes an air-tight seal with the flange of the funnel, the column of water thus being supported by atmospheric pressure. In setting up the instruments, the common practice is to hold the thumb over the end of the stem whilst filling to the polished edge of the funnel with distilled water, care being taken to release all air from the tube; the porous disc, previously soaked in water, is then slid over the mouth of the funnel, ensuring that no air bubbles are trapped between the plate and the water surface. Care must also be observed in handling the porous material to avoid altering the porosity of the surface.

In field investigations it is considered that the evaporating surface should be at the same height above ground as suggested for the collection of other microclimatic data, viz. 1.50 m. The instrument would not be satisfactory below 50 cm from the ground. It can be easily erected on temporary stakes, as shown in Plate 5, and although lateral displacement of the tube in a strong wind may occur, the evaporation surface will be displaced only slightly. By using a further retaining ring fitted further down the vertical tube, such displacement can be obviated entirely.

It is considered that a series of such instruments should be set up along a measurement line in the vicinity of a shelterbelt, in conjunction with anemometers where possible, and readings taken at similar time intervals to those used for the wind velocity data. In this manner the evaporation rate relationships between the various observation points can be related to the average wind velocity for a particular period at the same points.

(v) Soil Moisture Conditions

The importance of this factor must be held to vary considerably between regions according to the purpose for which shelterbelts are used, e.g. arable farming, soft fruit growing etc., and local climatic and soil conditions. As a feature of the microclimate to be investigated along with other influences of shelterbelts, the determination of soil moisture presents major experimental difficulties. Owing to the extreme variation in soil structure over very small areas, a considerable number of measurements are likely to be required in order to produce statistically reliable data. The field work implied in assessing soil moisture conditions within the zone of protection of a shelterbelt with a view to determing the effect of the belt on such conditions would appear to be extensive and, in the normal run of periodic studies of several shelterbelts and their sheltered areas, impracticable.

Methods used for the determination of soil moisture have been reviewed by Searle (1954). Although the weight loss after oven-drying soil samples taken in the field is still used as a measure of moisture content, this method has been generally superceded by the development of soil tensiometers and electrical resistance apparatus. Where detailed studies are contemplated, instruments of these types must be adjudged most suitable.

For the occasional comparative measurement of soil moisture relationships in sheltered areas, a simple method due to Dimbleby (1954) would appear to merit consideration, particularly as no expensive equipment is involved. Briefly, this method consists of opening new soil pits wherever measurements are required and inserting the points of porous "pencils" in the newly exposed profile at the appropriate depths, the distance the moisture travels along these "pencils" within a specified period being the measure of the available moisture in the soil. Dimbleby used cylinders, 12.5 cm long and 8 mm in diameter, with one end tapered similar to a pencil, cut from kieselguhr filter candles. After being graduated along their length in millimetres, using a waterproof ink, the "pencils" were dipped in a slightly acid solution of cresol red and oven-dried. As the water rose by capillarity up the "pencil" during use a simple pH change occurred from pink to yellow, thus giving a clear indication to the observer of the distance the water had risen. Within the limits of accuracy afforded by this method, useful information in ecological studies should be able to be obtained comparatively easily.

Section 2. Laboratory Investigations

Owing to the fluctuating atmospheric conditions encountered in nature and the inability to isolate any one feature of shelterbelt design, such as height, width and degree of penetrability, in field research, the tendency towards systematic model investigations, which can be easily controlled and reproduced, is understandable. The reliability of model research and the transfer of such results to field conditions has been the subject of considerable discussion. However, similar procedure has long been applied in the fields of aerodynamics, hydraulics and various branches of engineering practice and fundamental principles of model experiment, in the applicability to full-scale working, clearly established. It is evident therefore that experiments conducted with models in the laboratory can verify initially several basic principles of shelterbelt design and layout and, although not intended to replace studies under natural conditions, can save considerable time and expense in later field-work.

Laboratory investigations related to the shelterbelt question, particularly from a forestry aspect, are likely to be concerned mainly with the pattern of air flow and velocity reduction to windward and leeward of artificial barriers introduced into the air stream provided by a wind tunnel. Ideally, in the relation of wind-tunnel studies to field research, besides the geometric similarity between model and full-scale tests, the Reynolds number, R, should be of the same order of magnitude in both cases. If this condition is fulfilled, the laws of inertia and friction are altered in transition from model to full-scale working in similar proportion. In practice, however, it is not easy for similar Reynolds number to be provided in laboratory and field.

According to Reynolds' investigations (Ower 1949), there is a critical speed for the transition from laminar (steamline) to turbulent (eddying) flow in a fluid passing through a pipe, dependent on the dimensionless ratio,

$$R = vd/\nu$$

where v = mean speed of flow, d = pipe diameter and ν = kinematic viscosity = ratio of μ (coefficient of viscosity) to ρ (mass density). Applied to an object placed in an air stream,

$$R = Ud/\nu$$

where U = undisturbed velocity of the air and d = distance or length of object (Goldstein 1938).

The resistance encountered by an object immersed in a fluid is dependent partly upon boundary shear and partly upon separation and the consequent formation of a turbulent wake. The relative extent to which each of these will affect the flow varies with the Reynolds number characterising the motion and with the geometrical form and orientation of the body. It is possible to prove that, at a sufficiently high Reynolds number of flow, the drag coefficient is independent of the Reynolds number as well as the discharge coefficient (Woodruff and Zingg 1952). From this it may be inferred that similar flow patterns will be obtained about a given object if the flow is characterised by a sufficiently high value of R. This consideration is one of the first principles of wind-tunnel research.

A further complication arises in the comparison of model research with full-scale investigations of wind conditions. In nature, one is concerned with a fully developed boundary layer, the extent of which exceeds the height of the hedge or shelterbelt in question (Paeschke 1937, Geiger 1950). On the other hand, a mostly turbulent boundary layer is present in the wind-tunnel also although in the first stages of development, so that the barrier height surpasses the height of the boundary layer; to overcome this difficulty, long test sections are recommended for wind-tunnel studies (Blenk 1953). The differences between model and full-scale tests may be attributed very largely to the different turbulence in both cases (Nøkkentved 1938, 1940; Blenk 1952). Generally, wind-tunnel studies of velocity reduction leeward of a barrier have shown a more far-reaching zone of shelter than found in nature although exceptionally the reverse has been found to apply also Jensen (1954), by increasing the degree of roughness in a wind-tunnel, has adapted model-scale technique to overcome very largely the error due to turbulence differences.

Blenk (1952, 1953), comparing filed and laboratory observations of wind velocity reduction in the vicinity of shelterbelts as obtained by Nøkkentved (1938, 1940) and field data recorded by Nägeli (1943, 1946), suggests that quantitative conformity may be found between model and full-scale experiments provided distances measured from the shelterbelt are multiplied by the factor 0.5., i.e. the distance scale shortened by ½. However, he states further that this result must be considered as a provisional "rule-of-thumb" method and the conversion factor may depend also on the ratio of the Reynolds number to the height of the barrier, so that it may be somewhat greater for a hedge of 2 m in height than for a shelterbelt of 20 m high. In any case model investigations must be regarded as authentic in their qualitative results.

A possible criticism of much of the previous wind-tunnel research on shelterbelt influences is the doubtful suitability of the models used. It would seem unlikely that trees can be simulated successfully on a model scale, for example. Woodruff and Zingg (1953), in their investigations of shelterbelt cross-sectional profile, employed model trees and reversed several original designs in order to study the effect of different profiles on the pattern of air flow. In view of the materials used, it would seem probable that such alterations affected the degree of penetrability of the model belts and in this way introduced a further variable other than the one under observation. Any non-rigid material which is liable to change its shape under the force of the wind stream, and hence the degree of penetrability, must be considered unsuitable for wind-tunnel investigations which are to have a practical application in nature. Models should be constructed as far as possible so that, in an abstract form, they are representative of natural shelterbelts as regards their effect on air flow, whilst at the same time the variables involved can be adequately controlled or measured geometrically. The model used by Jensen (1954) to study the boundary layer over a wood and the restoration of the velocity field to leeward, consisting of corrugated paper mounted on a block of wood, cannot be considered as truly representative of natural conditions in view of the fact that the model was not permeable to wind at any level. Where two or more model fences have been put together to represent a wide shelterbelt (Blenk 1952), the series of continuous upper edges of the fences would doubtless have an effect on the wind pattern somewhat different from that produced by the tree crowns in a normal shelterbelt. These considerations would appear to indicate that models of shelterbelts should be penetrable to the wind in some degree and not completely solid, since the impermeable shelterbelt in the sense of a solid wall is not likely to be encountered in the field; they should be of uniform rigid construction throughout in all aspects except the one variable under observation; in representing the crown surface of a shelterbelt a continuous impenetrable model surface should be avoided; as far as possible they should be constructed of some simple, standard material which lends itself to repetition and continuity of the research.

Experimental techniques for velocity measurement in wind-tunnel investigations have become reasonably standardised. The design and characteristics of pitot-static and total-head tubes have been discussed in detail from theoretical and practical considerations by Goldstein (1938) and Ower (1949). In view of the small scale of models used in wind-tunnel tests and the detail of velocity distribution frequently required, it has become customary to use very fine total-head tubes made from hypodermic tubing. Such total-head tubes indicate the true total head provided that the ratio qa/ν is greater than 30, where q=air speed, a=radius of mouth of tube and ν=kinematic viscosity of the air (Goldstein 1938). A further practical consideration is that, with very fine hypodermic tubing, only short lengths should be used in order to minimise the lag which results; also the tube should be sufficiently rigid as to avoid excessive vibration when exposed to the air stream.

Pressure measurements, from which velocity values are calculated according to the equation,

$$p=\tfrac{1}{2}\rho v^2$$

where p=pressure, ρ=density of air and v=velocity, are commonly observed by means of manometers, various types being available. Probably the most suitable form of manometer is the inclined-tube, magnification of the registered pressure being available in the ratio $1/\sin\alpha$, where α=angle of inclination of the tube; its sensitivity is recorded as 0.002 in. of water at an inclination of 5° (Goldstein 1938).

It is most convenient to express wind-tunnel measurements as horizontal velocity ratios, i.e. the ratio of the velocity measured at a point in the tunnel with the model in position to the velocity measured at the same point in a clear tunnel, and not in relation to the speed in the tunnel above boundary layer influences. This procedure is analogous to that generally adopted for velocity measurements in the field.

In conclusion, it would appear that wind-tunnel investigations of shelterbelt problems should be regarded as a basis for subsequent investigations in nature and their practical application to field research should be borne in mind when formulating a programme of laboratory studies.

PART THREE

DESCRIPTION AND RESULTS OF RESEARCH UNDERTAKEN

Chapter 8

PLAN OF THE WORK UNDERTAKEN

THE PROVISION of shelter in the form of tree belts is essentially a practical forestry problem. The design, establishment and maintenance of the structure of shelterbelts in order that they may afford, in their vicinity, an efficient degree of protection appropriate to their particular function. whether the latter be in connexion with agriculture. horticulture or afforestation, demand a very specialised forestry technique. General principles relative thereto may be obtained from the study of the effects which shelterbelts exert on climatic factors and the associated biological influences. This conception has formed the basis of the research undertaken.

In this particular research project, under terms of reference which provided for the investigation of the effects of shelterbelts on microclimate, the available scientific evidence concerning such effects and the influences of shelterbelts on agricultural yields and forestry practice has been reviewed and presented in the foregoing chapters. The applicability of previous research to shelter requirements in Great Britain and the possible development of research from a forestry aspect have been considered in the light of such evidence. Since development of exposed hill and upland areas and intensification of land use in these districts suggest the greatest potential extension of shelter planting in this country, the ultimate aim of the research may be regarded as the determination of the site, type, structure and silvicultural composition of shelterbelts which would provide the most efficient shelter, particularly in connexion with stock-rearing and afforestation on such areas. The study of shelterbelt design and maintenance on lowland and upland arable areas must be included since certain basic features are common to all fields of shelterbelt employment and also because the improvement and treatment of existing belts in these regions are matters of immediate importance.

The evidence of previous research reveals that the positive influence of shelterbelts on various microclimatic factors has been established experimentally. As a result of detailed research in other countries certain general conclusions regarding shelterbelt design and layout have been derived. Therefore, it has seemed appropriate to concentrate further research on the utilisation and augmentation of microclimatological data from the point of view of ascertaining the most suitable geometric proportions for shelterbelts and also as a means of studying structural composition of belts in relation to sheltering efficiency.

The research presented herein has formed the preliminary stage of a comprehensive research programme, formulated in 1953 after completion of the preparatory work, which involved especially the detailed examination of experimental technique and instrumentation for the comparative study of various elements of microclimate—wind velocity and direction, atmospheric temperature and humidity, evaporation, transpiration, soil moisture and temperature. The proposed investigations included the study of the influences on microclimate, particularly on wind velocity, of existing shelterbelts of different width, structure and composition by species and development stages, with a view to determining the optimum belt structure; the study of wind conditions in regions of irregular topography, with a view to determining the most suitable situation for shelterbelts to ensure maximum protective efficiency; the consideration of the application of shelterbelts to forestry practice, both in the provision of shelter on exposed sites scheduled for afforestation and of protective margins and internal wind-firm belts in the established forest.

In the study of shelterbelt structure, it is evident that a very large sample of belts would be required to give general conclusions, owing to the complexity of the geometric and biological variables involved. In addition, long-term investigations would be necessary before exhaustive information on the inevitably slow process of developing appropriate structures, by means of planting and subsequent treatment, could be expected. Although certain conclusions may be obtained from a purely physical approach with controlled experiments, the majority of information of practical forestry value must be derived from field studies. In this connexion a means of assessing the efficiency of different belt structures has been considered desirable.

The field investigations have been directed towards this end and the efficiency of the selected shelterbelts assessed on the basis of their effect on the microclimates of adjacent regions. Wind velocity reduction, being the primary effect on which other microclimatological characteristics of sheltered areas are dependent to a greater or lesser extent, has been investigated more thoroughly than other physical factors. Since evaporation rate integrates wind, temperature and atmospheric humidity conditions and their continual fluctuations and is adjudged particularly suitable for the comparative assessment of microclimates within the objects of this research, more attention would have been paid to this factor than to individual elements such as temperature and humidity. However, because of difficulties with equipment, insufficiency of data has precluded this possibility. Few studies of atmospheric temperature and humidity were conducted, owing chiefly to the difficulties of experimental procedure and the anticipated small value of the results, the latter arising from the extreme variability of ground and plant cover conditions near the shelterbelts. For these reasons, wind abatement must be considered the most reliable index to the protective value of belts.

The shelterbelts examined in this paper are located within reach of Edinburgh and have been selected mainly for convenience but also because the variety of belt types encountered in the Lothian valleys, the Pentland, Moorfoot and Lammermuir Hills present a fairly comprehensive range, representative of similar types throughout Britain. The number of belts studied in detail has been unavoidably restricted by the difficulties associated with any field research dependent on particular meteorological conditions and also by the unsuitability of many shelterbelts for the comparative evaluation of their sheltered environs. Delay in obtaining the required equipment and evolving appropriate experimental techniques has imposed further limitations.

Owing to the high cost of field research and the difficulty of isolating many of the dimensional variables in shelterbelt design under natural conditions, many of these variables have been investigated by previous workers with the aid of model research in field and laboratory. In this way the influence on the pattern of air flow and the extent and nature of the shelter effect attributable to the length, height and degree of penetrability of windbreaks have been clarified. In order to support field investigations and promote the silvicultural interpretation and analysis of the results, studies of certain additional fundamental problems related to shelterbelt design, which were thought to be of particular interest to shelterbelt technique in this country, were carried out in this programme. In view of the probable importance of these aspects with regard to shelter planting on upland areas and to forest margins, wind-tunnel investigations of the effect of shelterbelt width and cross-sectional profile in determining the leeward extent of the sheltered zone were undertaken at the Department of Meteorology of the Imperial College of Science, London, where facilities were made available. It was intended that the wind-tunnel studies should form a basis for subsequent research in the field and that, although the results of laboratory studies of this nature may be considered to have a qualitative application to natural conditions, these studies should be substantiated by field experiment. However, suitable experimental areas have not yet been located.

The desirability of intensive study of air flow near the ground in regions of varying topography has been mentioned earlier from the point of view of achieving maximum efficiency of shelterbelts through careful siting. It must be accepted that conclusions drawn from a few individual studies of wind conditions in upland districts would only rarely permit a general application to other areas, owing to the diversity of meteorological and topographic conditions. This question is discussed on the basis of observational and recorded evidence in Chapter 12.

The field studies of shelterbelts and the wind-tunnel investigations of cross-sectional profiles in model windbreaks are interpreted in relation to the application of shelterbelts to forestry practice in Chapter 13.

The experimental results presented in Chapters 9 and 10 may be sub-divided as follows:

(i) Laboratory investigations of wind conditions in the vicinity of model windbreaks of different width and cross-sectional profile;
(ii) Field investigations of microclimatic factors, particularly wind velocity, in the vicinity of different types of shelterbelt.

The practical application of these results to shelterbelt design and maintenance is examined in Chapter 11.

Chapter 9

LABORATORY INVESTIGATIONS OF WIND CONDITIONS IN THE VICINITY OF MODEL WINDBREAKS

WIND-TUNNEL STUDIES of certain fundamental problems related to shelterbelt design were carried out during January 1955, facilities being provided by the Department of Meteorology, Imperial College of Science and Technology, London.

The two main aspects of investigation were the relation of shelterbelt width to the extent of the sheltered zone on the leeward side of the barrier and, similarly, the effect of the cross-sectional profile through the entire width of the windbreak. In addition, observations of wind velocity reduction were made in the vicinity of two parallel windbreaks set some distance apart, behind a scale model of a natural coastal shelterbelt and a further model representing a spaced-group arrangement of trees throughout the belt instead of the conventional, overall, planting pattern.

The models were introduced into the air stream provided by a wind-tunnel and wind velocities obtained for individual measurement points by recording dynamic and static pressures and subsequent calculation employing a recognised formula for the pressure/velocity equation. A total of 21 series of observations was obtained with the different models, each series involving measurements at three elevations above the tunnel floor and at up to 13 horizontal distances down-wind of the models.

Procedure

The tunnel used had an overall length of 30 ft. and was octagonal in cross-section. The DC motor, operating a twin-blade propeller, could be controlled by a rheostat and constant wind speeds maintained with reasonable accuracy during the investigations.

The test section of the tunnel, extending for only 66 in., restricted the range of velocity measurements down-wind of the models to some extent. The octagonal construction allowed a floor width of 15 in., the section widening to 36 in. in diameter through the axis of the tunnel. Because of the sloping walls, the models could not be constructed to fit the total width of the tunnel exactly with the materials used for their manufacture. However, it is unlikely that these limitations affected the qualitative value of the results to any significant degree.

In order to avoid permanent structural alterations to the tunnel and in view of the fact that the models required to be secured firmly to the tunnel floor and also that a simple means of moving and setting the measurement apparatus was desirable, a false floor was constructed for the test section to incorporate the base of each model and the pressure-measuring instruments (Plates 6-8). This base-board consisted of two 1-in. planks, arranged parallel to one another but separated by a narrow channel to permit movement of the pitot apparatus along a central measurement line. The planks were permanently overlaid with ¼-in. plywood at the down-wind end as illustrated; the remaining area was reserved to accommodate the individual bases, also of ¼-in. plywood, of the models so that "steps" in the tunnel floor were avoided. Since the largest model used extended for 30 in. (75 cm) along the test section, an equivalent distance along the planks, measured from the up-wind edge, was left exposed in this way. For smaller models, so as to complete the smooth surface of the artificial floor and also to cover the central channel before and behind the measurement apparatus, plywood "filler pieces" were prepared to meet the requirements of each experiment (Plate 6). The bevelled outer edges of the base-board fitted the sloping walls exactly, thereby increasing the effective floor width to slightly more than 17 in. When fitted in the tunnel, a shallow gradient was added at the ends to prevent disturbance in the air stream.

A sliding device was made to facilitate horizontal movement of the pitot apparatus along the channel provided. With the filler pieces mentioned, the apparatus could be fixed at any distance in multiples of 2 in. (5 cm) along the working section.

With this equipment a regularly smooth surface could be maintained throughout. Any small gaps between the plywood sections, caused by shrinkage, were carefully sealed with adhesive tape between each series of experiments. All screws were countersunk and, where necessary, the holes smoothed over with moulding clay.

Uniformly spaced wire nails were used for the construction of the models. The reasons for the selection of this material were several: with rows of nails a uniform decrease in penetrability to the wind with increasing width (i.e. number of rows, arranged normal to the direction of flow) could be expected; the rigidity of the nails would obviate penetrability changes due to alteration of form under the wind pressure as frequently found with flimsy material; the points of the nails, directed upwards, would not present a continuous upper surface of the model and, in this respect, would represent more nearly the permeable tree crowns, producing a series of small eddies as occurs above a crown surface in woodlands; such material is readily obtainable and inexpensive, so that models can be reproduced or modified easily for further investigations, thus favouring the continuity of similar research. Owing to the difficulty of simulating trees on a model scale, it was considered preferable to employ windbreak models, where air-flow conditions could be anticipated to be similar in their vicinity to those encountered in nature, but which also allowed maximum control of the variable factors involved. In this way the models employed may be regarded as model shelterbelts in an abstract sense only but the qualitative value of the results must be credited as applying to living belts under ideal, though probably rare, natural wind conditions. This fundamental approach is necessary in order to isolate many of the variable features of shelterbelt design.

Nails 2¼ in. in length were used, the heads being countersunk in the underside of the model base, so that the part projecting above the upper side of the base was 2 in. (5 cm) in length, this being the height decided upon as standard for the models. In all models the first row of nails started 1 cm from the edge of the base, the rows were 1 cm apart and the nails spaced at 1 cm within the rows. An echelon arrangement, similar to that used in forest planting operations, so that the nails in one row were opposite the spaces in the next, allowed alternate rows of 42 and 43 nails respectively. Models were constructed with depths in multiples of height, e.g. 1, 2 and 5 heights (h). Thus, the 1h wide model, width here referring to the extent in the direction of air flow, consisted of 4 rows of nails, the 2h model of 9 rows and the 5h model of 24 rows. Under natural conditions the width of a shelterbelt is considered as the distance between perimeter fences or hedges and not the distance between the stems of the two outermost rows of trees; a similar classification has been adopted therefore for the model investigations.

In connexion with the studies of varying model width and their effect on the wind velocity pattern, six models were constructed with uniform height throughout (5 cm). The range of models, of widths in multiples of 1h, 2h and 5h, permitted the study of width in any unit of height (h) up to a maximum of 15, e.g. a 7h wide model resulted from the combination of a 2h and 5h model. For the investigations of the effect of different cross-sectional profiles on wind abatement, models, 1h and 2h wide, were prepared with sloping upper surfaces. In the 1h wide models, the height of the nails ranged from 2 cm in the first row to 5 cm in the fourth row, representing for all practical purposes a gradient of 45°. In the 2h wide model, the nail height was 1 cm in the first row and 5 cm in the ninth row, representing a slope of 30°. All nails used were of similar gauge, approximately 0.3 cm in diameter. The spaced-group model consisted of 3 rows of groups, arranged on a 5h wide base; each group was composed of 19 nails at a spacing of 1 cm with the groups at 8 cm centres across the tunnel and 8.5 cm (vertical interval) along the tunnel. In this manner the model comprised 4 complete groups and 2 incomplete groups at the edges in each of the outer rows, the centre row contributing 5 complete groups. The number of nails amounted to 311, corresponding to approximately 7¼ rows in the regular models. The group arrangement is illustrated in Plate 7, Fig. 20, and Fig. 38.

The remaining model, representing a natural wind-pruned shelterbelt on the East Lothian seaboard at Gosford, which is described later, was constructed with a solid plate, 1.375 cm in height, at the windward edge; the leeward edge, 5 cm in height, and the sloping surface being covered with perforated, galvanized gauze. The overall width of the model was 20 cm, the effective width being 19 cm; with a scale of 1 cm to 8 ft, this corresponds approximately to the width of 150 ft in the natural belt.

Pressure measurements in the tunnel were made by means of small total-head tubes (Plate 7). It was intended originally to employ six such tubes, arranged vertically between ½ and 5½ cm above the tunnel floor, as illustrated. It was found later that the time lag due to the fine bore of the tubing had to be reduced and a further apparatus of only three total-head tubes was prepared from hypodermic tubing of larger bore, the external diameter being 1 mm. These were arranged at 1 cm (0.2h), 3 cm (0.6h) and 5 cm (1.0h) above the floor, their lower ends passing through a rubber stopper in the sliding device previously mentioned and connected by means of polythene tubing, which ran along the channel provided and through a central hole in the original floor, to a differential alcohol manometer. A simple arrangement of taps allowed each total-head tube to be connected in turn to the one manometer. Static pressure was determined by means of a side-static hole in the wall of the tunnel connected to the other arm of the differential manometer. The inclined-tube manometer, manufactured by Rosenmüller of Dresden, was filled with alcohol of specific gravity 0.8 and inclined to give a magnification of x10.

Before the experiments were undertaken, tests were carried out using standard pitot-static tubes to determine the correction to be applied to the final manometer reading, due to the fact that the static pressure recorded at the side-static hole was not necessarily the same as the actual static pressure at the same point at which the total-head tube registered the sum of the kinetic and static pressures. Series of readings were made, with and without the models in position, to ascertain the gradient of static pressure along the tunnel; corrections were made to the final pressure readings where necessary. The side-static hole was situated some distance along the working section, in order to avoid the zone of greatest disturbance caused by the models, since the presence of a velocity component not parallel to the wall of the tunnel at this point would have falsified the static pressure reading. Whilst there are certain disadvantages with using the total-head and side-static combination, it is considered that this method is to be preferred to the use of small pitot-static tubes in investigations of this nature. During pressure observations within the range of the model, the static pressure recorded by the static part of the pitot-static tube would rarely represent the true static pressure, owing to disturbance in the air stream.

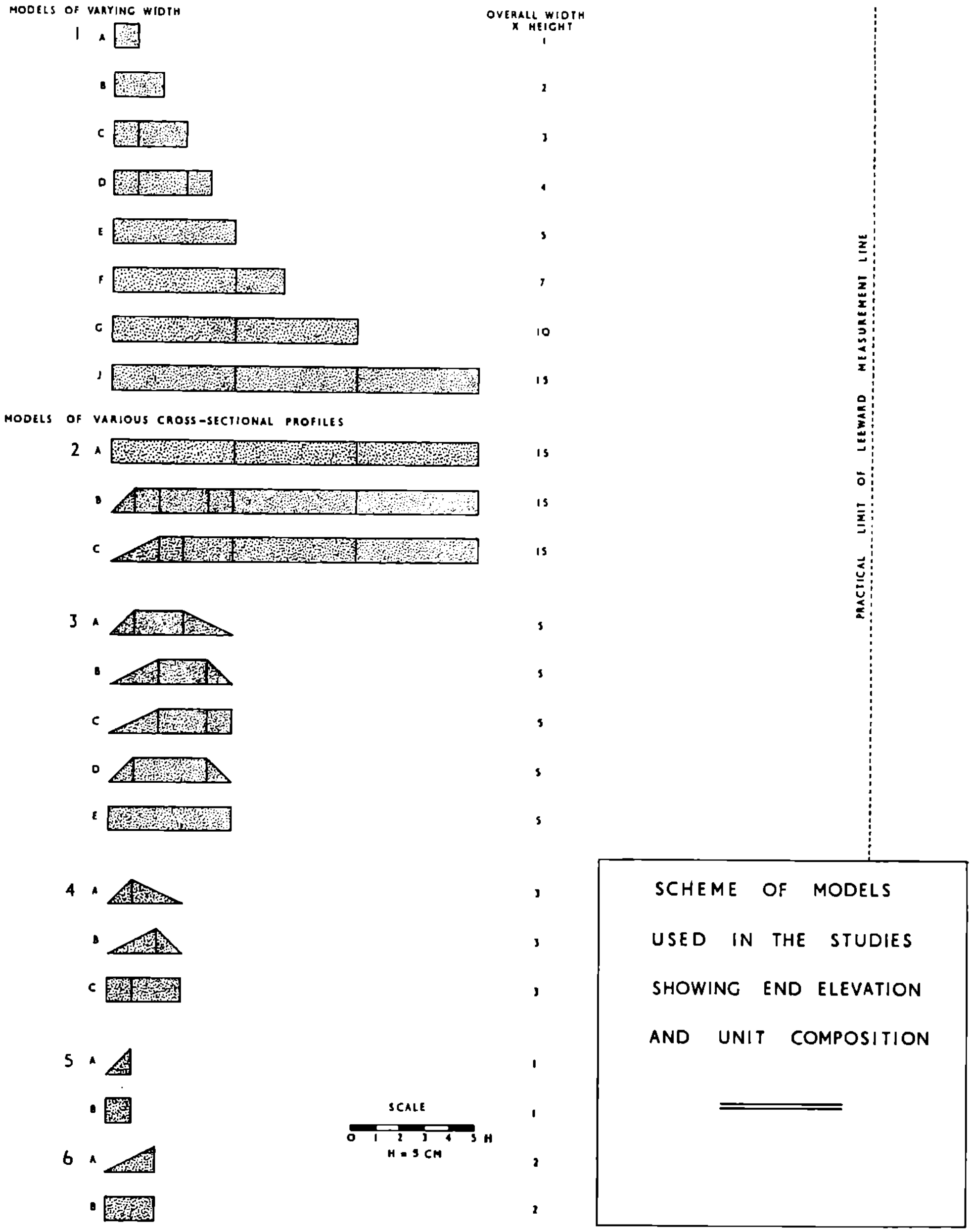


FIGURE 20. Scheme of models used in the studies, showing end elevation and unit composition.

Throughout the experiments the tunnel was maintained at a constant speed of 10.61 m/sec (34.7 ft/sec). Both before and after the model studies, the pressure gradient along the clear tunnel, i.e. with no models in position, was determined. For this purpose the whole of the base-board was covered uniformly with plywood. All later pressure measurements were related to the pressure registered at the same point of measurement in the clear tunnel. Thus, relative velocities have been expressed as horizontal velocity ratios v/v_o, where v and v_o are the respective velocities of the wind at a particular point with and without the model in position, for three values of z, the height of measurement above the tunnel floor. The velocity ratios were obtained from the equation:

$$\frac{v}{v_o} = \sqrt{\frac{p}{p_o}}$$

where p and p_o are the corresponding values of the differential pressures. This equation presupposes a constant value of ρ, the density of the air. The temperature and barometric pressure in the laboratory were observed frequently and indicated that a constant air density could be assumed within the limits of accuracy of pitot tubes and manometers. In the plotted results the horizontal velocity ratios have been shown as percentages to conform with the results of field experiments.

During the experiments it was necessary to allow an interval between reading owing to the inevitable time lag produced by the small total-head tubes and also to avoid fluctuations which arose when the tunnel was switched on. In practice, the manometer was observed constantly and only when the alcohol column remained stationary or the pulsations were confined to very narrow limits on the scale was the reading recorded; this generally involved a delay of 3-5 minutes between individual observations.

To illustrate the flow patterns when the various models were in position in the tunnel, smoke from a paraffin oil vaporiser was introduced into the air stream. Unfortunately, the structure of the tunnel did not allow the streamlines produced to be viewed horizontally along the test section of the tunnel or to be photographed and it was impossible, therefore, to trace the course of flow immediately to leeward of the models. It was observed, however, that there was no significant lifting of the streamlines as the air stream passed over the wider models.

Results

The results of the wind-tunnel investigations are

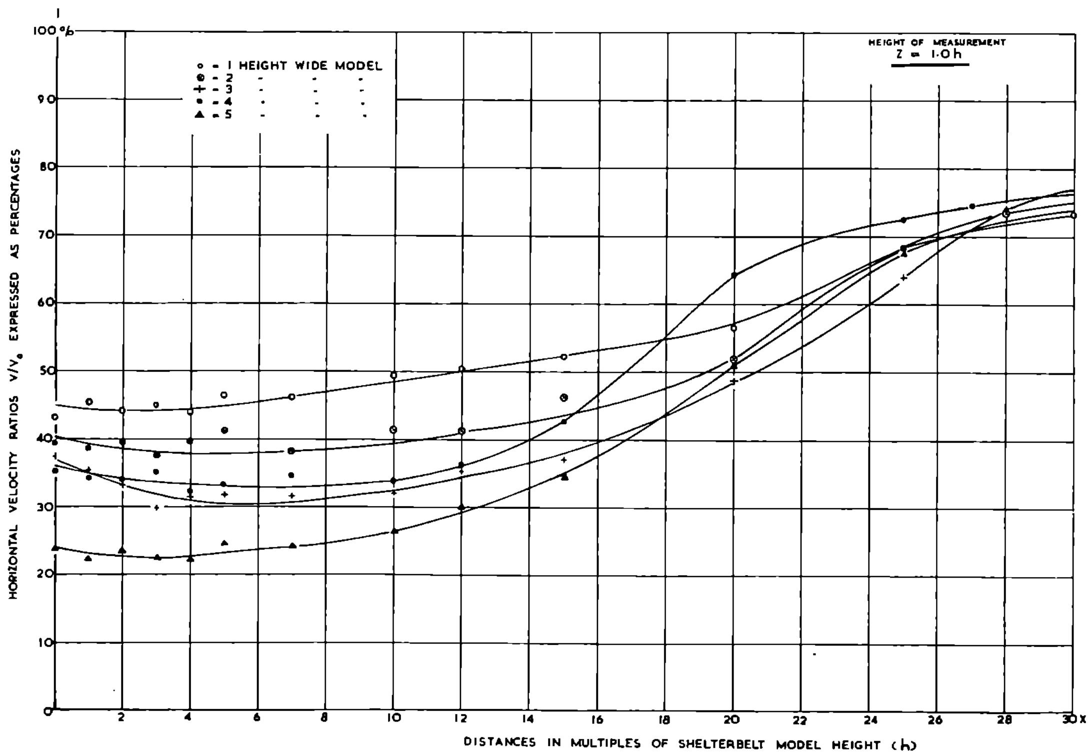


FIGURE 21. Relative wind velocities to leeward of models ranging in width between 1 and 5 times the model-height. Measured at the height of the models above the tunnel floor.

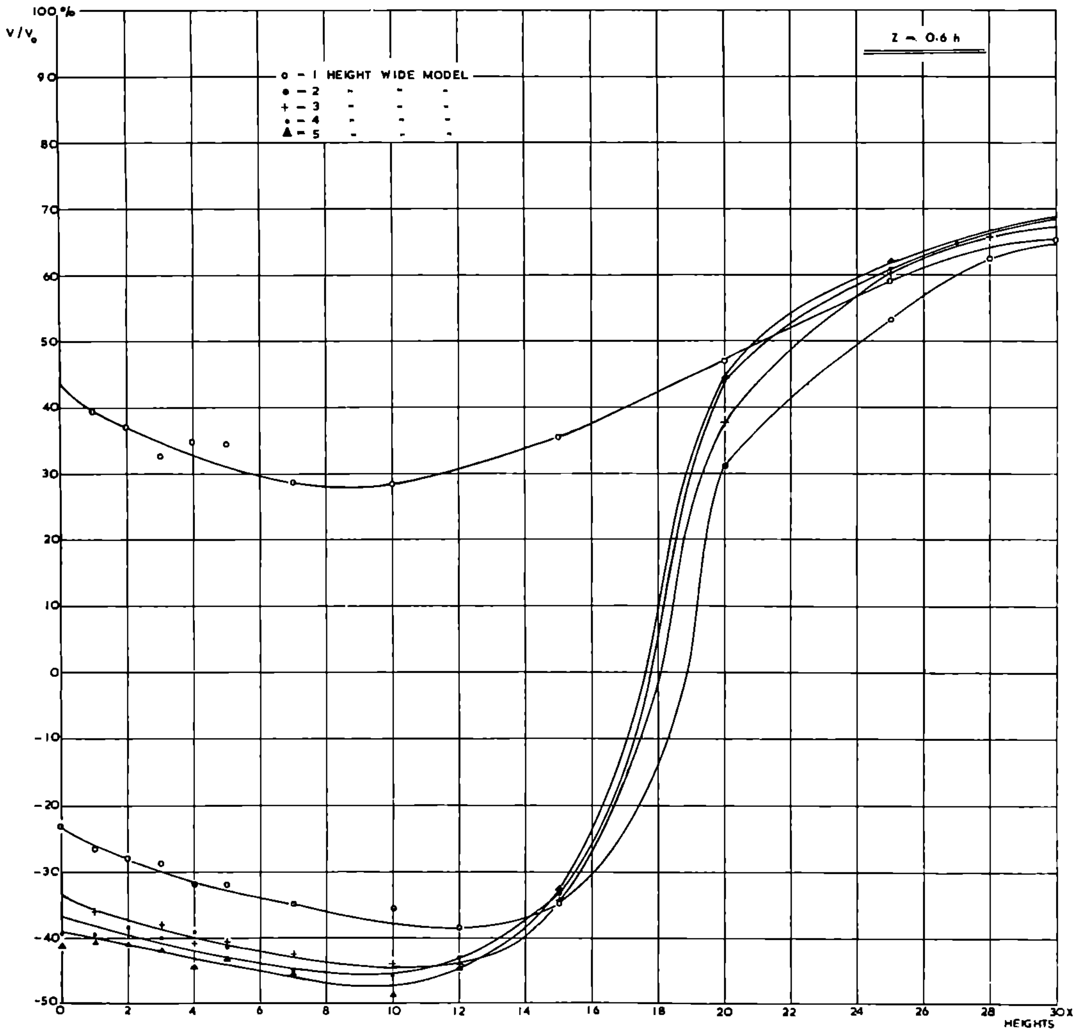


FIGURE 22. Relative wind velocities to leeward of models ranging in width between 1 and 5 times the model-height. Measured at 0.6 × the height of the models.

shown in Figs. 21-35 and Tables 1-6. Tables 1-3 give the values of wind velocity as determined experimentally for each point; Tables 4-6 show the smoothed curve values corrected to the nearest percentage. In the graphs, the abscissae represent distances in multiples of the model height (5 cm) measured from the leeward edge of the model; thus, the position 0 varies according to the width of the particular model. The ordinates represent the horizontal velocity ratios, v/v_o, expressed as percentages. Results are shown separately for the different ratios of z/h: 1.0, 0.6 and 0.2. (See p. 86-95 for tables.)

A preliminary survey of the results shows that the curves of wind velocity abatement at 0.6h and 0.2h reveal a very similar pattern. This is in agreement with the conclusion that the shelter effect at all distances behind perforated screens is independent of the height above the base so long as it is less than 0.6 times the height of the screen in a smooth tunnel and 0.4 times the height of the screen in a rough tunnel (Jensen 1954). Outdoor model experiments have shown that the wind velocity reduction was of much the same pattern below 1h with a dense screen but greater divergence between curves for 1h, ½h and ¼h was to be found with penetrable screens (Nägeli 1953a). Again, this is revealed in the studies of the narrow and more penetrable barriers in this series.

Of particular interest are the curves at elevations of 0.6h and 0.2h in respect of all models wider than 1h. In all these cases, the values recorded immediately to leeward of the models are negative; the sign in this instance refers merely to the direction of the wind. The total-head or pitot tube measures a pressure due to the horizontal velocity component approaching the mouth of the tube. The negative differential pressures registered imply the development of a low pressure area immediately behind these barriers, resulting in a reverse directional flow or eddying, which has been shown in previous research to occur with dense and fairly dense screens. In similar investigations in Germany, Blenk (1953) records that with the apparatus available it was impossible to measure these negative values obtained near dense barriers and positive values only are treated in the results shown. Nøkkentved (1938) has examined the relationship between penetrability ("hole area") and shelter effect and found that, with dense screens of penetrability 0%, negative values occurred up to about 10 heights to leeward of the screens; this he attributed to marked eddying. With a screen of penetrability 26%, eddies also formed but of materially slighter intensity; in this case, the eddy zone extended to 12.6h, after which positive values of wind velocity appeared. Similarly, Jensen (1954) commences the shelter effect curves for screens of 0

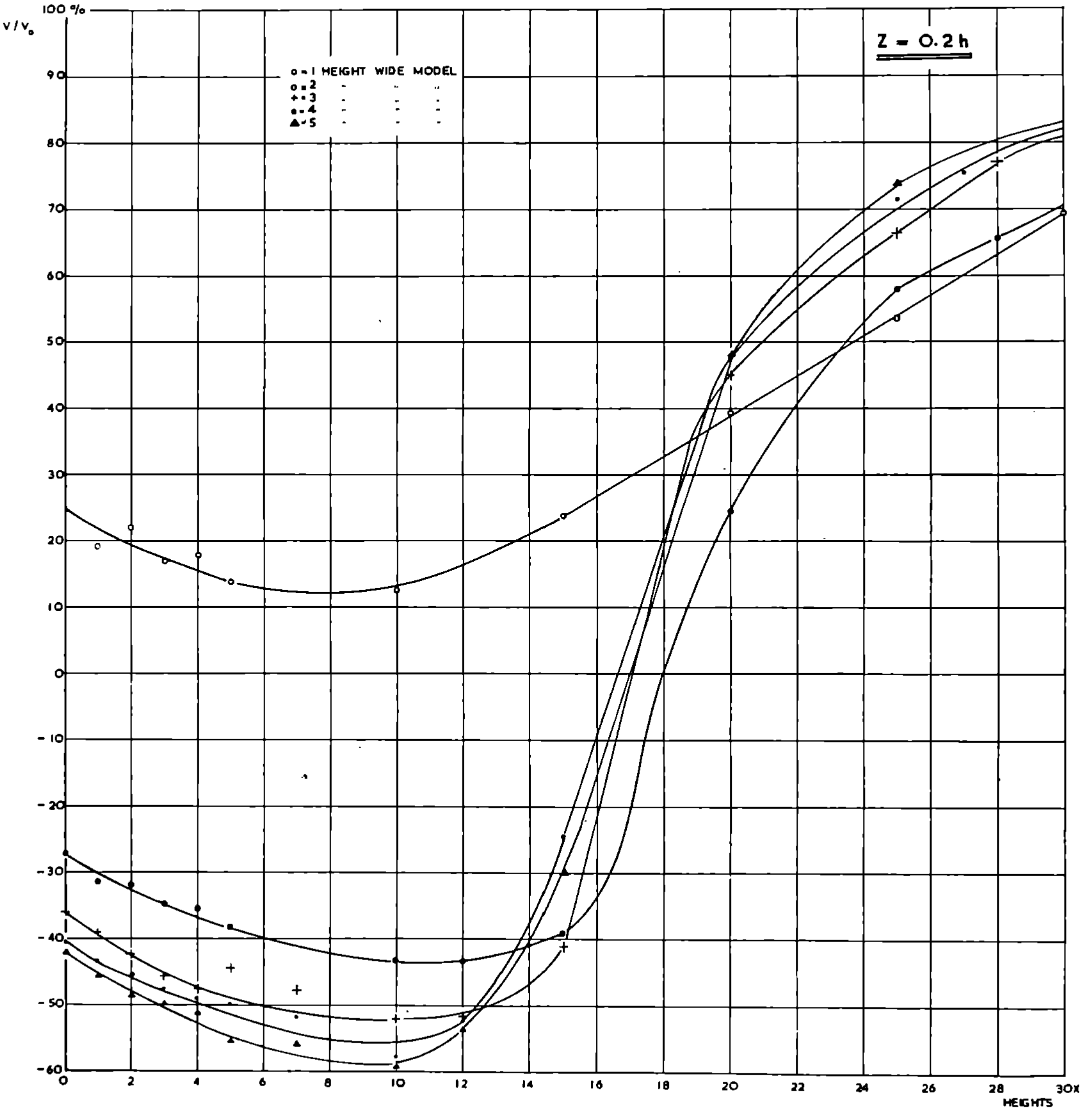


FIGURE 23. Relative wind velocities to leeward of models ranging in width between 1 and 5 times the model-height. Measured at 0.2 × the height of the models.

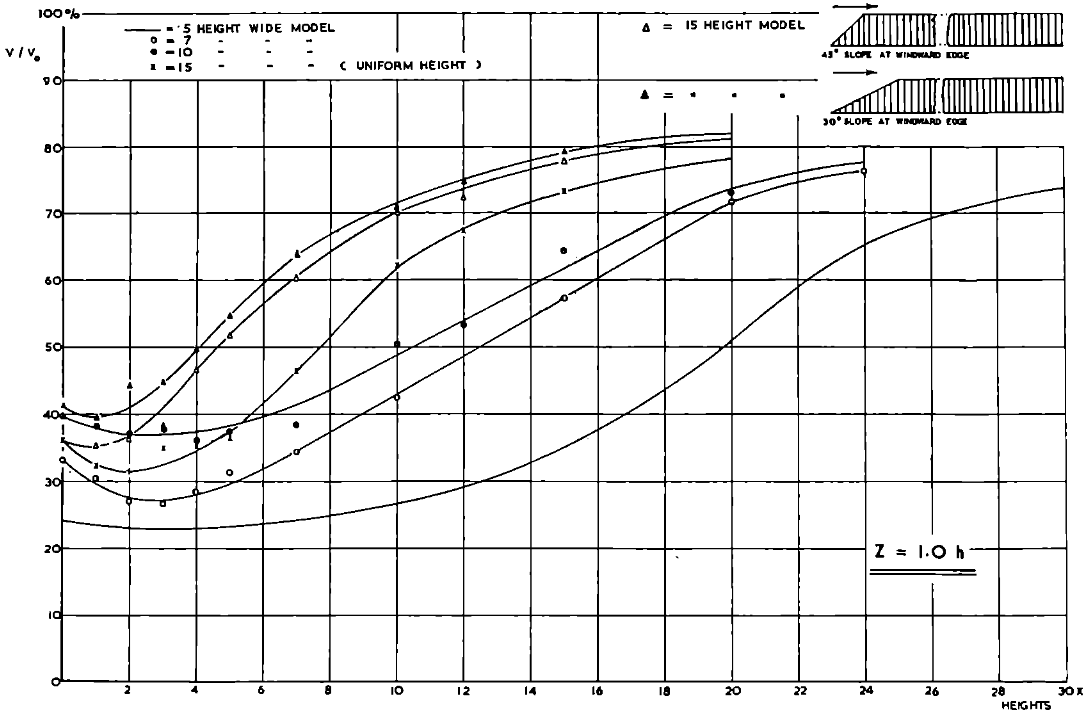


FIGURE 24. Relative wind velocities to leeward of models ranging in width between 5 and 15 times the model-height, illustrating also the effect of the form of the windward edge in the case of three models, 15-heights wide. Measured at the height of the models.

and 26% penetrability at the limit of the eddy area, i.e. 13-14h to leeward; with screens of penetrability above 38%, no significant eddying was found. Thus, the presence of negative wind velocity values, indicating eddying, behind barriers of low penetrability has been clearly established by earlier workers but these values do not appear to have been included in any of the results.

In the graphs illustrated here it has seemed reasonable to show these negative values where they have been recorded because of their smooth trend. The magnitude of the negative depression would appear to throw some light on the nature of the low pressure area which gives rise to the eddying, whilst the points at which positive values appear clearly illustrate the extent of the disturbed zone behind the various models and, in this way, have a distinct relation to their effect on air flow and consequent protective efficiency. It is evident also that the models of widths greater than 1h used in these studies approached the impenetrable barriers of earlier research, in spite of their apparently open structure.

Calculating the blockage ratio of one row of nails from the product of the diameter and height of the nails and the average number of nails per row in proportion to the total frontal area, one such row has a geometric penetrability of approximately 72%. It has been impossible to determine mathematically the degree of penetrability exhibited by a series of parallel rows although, as previously stated, a uniform decrease in penetrability with increasing number of rows might reasonably be expected. Since no negative values have been recorded for the 1h wide model (Figs. 21-23), it may be assumed that the degree of penetrability of four parallel rows of nails is not less than about 30% and, by comparison with Jensen's (1954) results, is probably about 35%. However, in the 2h wide model, composed of nine rows, the degree of penetrability is obviously less than 26%.

Had various narrow screens of predetermined penetrability to the wind been observed in the wind-tunnel, it might have been possible to allot specific penetrability ratios to the different models employed in these studies by comparison of the wind velocity curves obtained. At the same time, it would have proved difficult to apportion accurately the velocity abatement due to the penetrability and that which may have arisen through the different pattern of air flow over the wider models. In these investigations, therefore, penetrability and width can only be studied in the aggregate and not individually. From a practical point of view it is this combination with which we would be concerned in field research also and not the separate variables.

The Effect of Shelterbelt Width on the Sheltered Area

The results of the studies of wind velocity to leeward of models varying between 1h and 15h in width are illustrated graphically in Figs. 21-26 and in tabular form in Tables 1-6 and are compared separately for each height of measurement above the tunnel floor. (See p. 86-95 for tables.)

Considering the width range 1-5h, the wind velocity values recorded at the height of the model (z=1.0h=5 cm) show that, as far as 15h to leeward of the models, the degree of velocity abatement increases as the model width increases from 1h to 5h (Fig. 21). Beyond this point the acceleration of the wind becomes more marked the wider the model; this fact is illustrated particularly by the curve for the 4h wide model. However, the percentage wind speed values measured at a horizontal distance of 30h from the models vary between 73% and 76% only, indicating little difference in the protective effect of the five models at this elevation.

At 0.6h (3 cm) above the tunnel floor (Fig. 22) there is again little difference between the various curves over the leeward distance range of 20-30h. Owing to its higher degree of penetrability to the air stream, the 1h wide model does not cause reverse currents giving rise to negative velocity ratio values

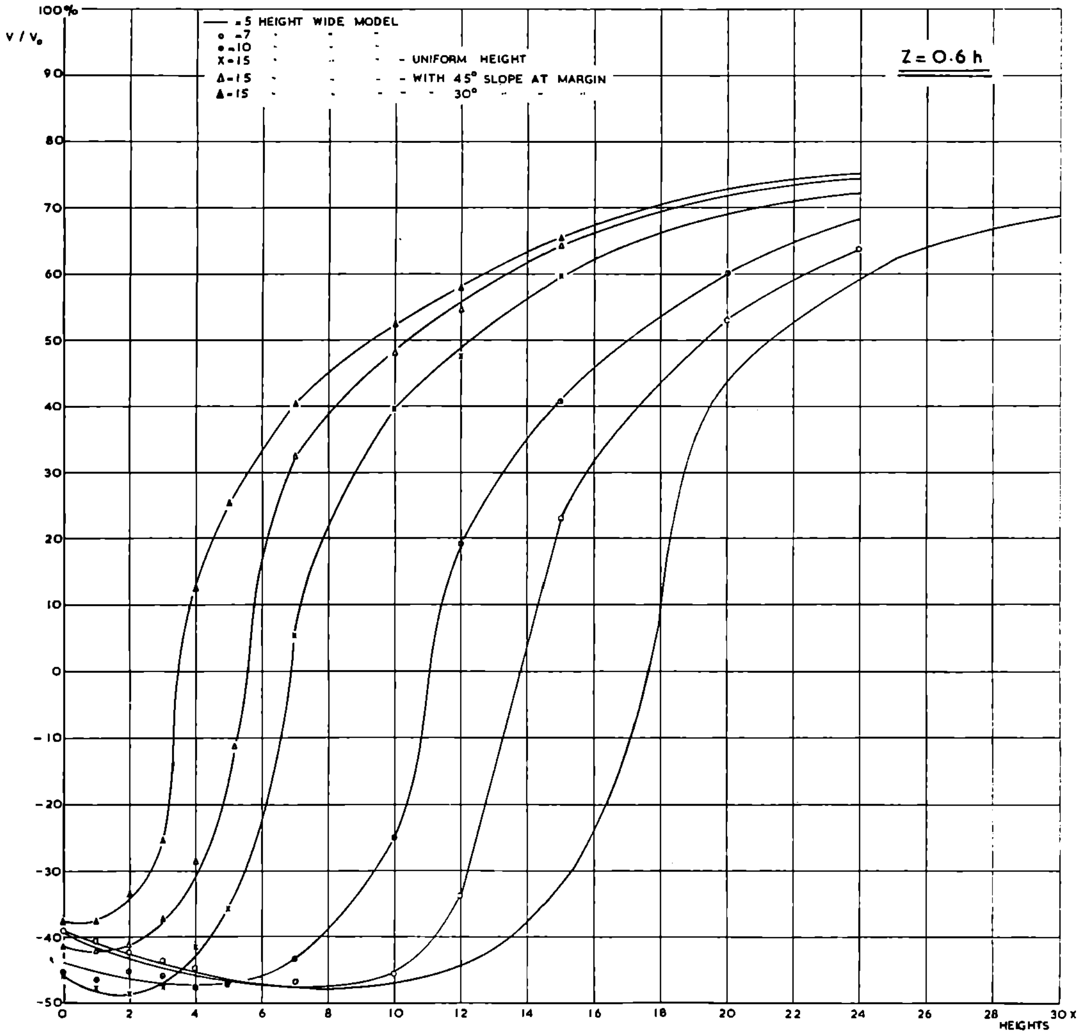


FIGURE 25. Relative wind velocities to leeward of models ranging in width between 5 and 15 times the model-height, illustrating also the effect of the form of the windward edge in the case of three models, 15-heights wide. Measured at 0.6 x the height of the models.

as found with all models of greater width and, consequently, lower penetrability. The negative depression of the 2h curve is not of the same order of magnitude as in the case of the 3h, 4h and 5h wide models but it will be observed that there is little variance between the last three curves, both over the extent of the eddy zone and in the gradient of velocity resumption beyond. With the 2h wide model the distance protection is somewhat greater than with the wider models; small decreases in efficiency can still be observed however as the model width increases from 3h to 5h.

The measurements recorded at an elevation of 0.2h (1 cm) above the tunnel floor (Fig. 23) are very similar to those recorded at 0.6h throughout, except that the divergence between the various curves is somewhat more pronounced, particularly at distances greater than 20h to leeward of the models. This may be attributed to the difference in the boundary layer development over this distance.

In the wider group of models, 5-15h, the differences between the curves are more marked. At an elevation of 1.0h above the datum (Fig. 24) not only are the relative velocities immediately to leeward of the models considerably higher for widths of 7-15h than for the 5h wide model but the curves of velocity resumption become progressively steeper with increasing model width and, thus, the distance protection correspondingly less. Compared with a wind speed of 34% of the unobstructed velocity at a point 15h down-wind from the 5h wide model, the corresponding values for the 7h, 10h and 15h wide models are 57, 62 and 74% respectively. It is unfortunate that the tunnel did not allow a longer measurement line in the case of the wider models and permit further comparison.

At an elevation of 0.6h, the variation between the different curves is very prominent (Fig. 25), both in the extent of the zone of reverse flow immediately behind the models and in the gradient of the curves beyond the eddy zone. At 0.2h above the tunnel floor similar conditions are produced (Fig. 26).

The results suggest that, with these particular models, the width of 5h is critical. Models below 5h in width register a somewhat increased shelter effect with increased width at the level of the model height although this higher degree of shelter extends for a limited distance only (about 15h). After this point the curves at the 1.0h elevation show a similar shelter effect with only a slight tendency to decreased efficiency with increased width. In the case of models wider than 5h, different conditions arise; higher velocities obtain behind the models and the unobstructed velocity is regained more rapidly the wider the model. In this way there is a very pronounced decrease in the shelter effect to leeward of the wider models. This fact suggests that the wider models, i.e. those greater than 5h in width, tend to lead the air stream parallel to the upper surface of the model and to reduce the upward deflection of the stream, which is known to occur with narrow barriers of low penetrability.

The significance of the width of 5h may be the degree of penetrability exhibited by this particular model's construction. The leeward shelter effect behind a barrier is determined chiefly by the barrier height and penetrability to the wind and, with a constant barrier height, the shelter effect diminishes rapidly as the degree of penetrability is decreased until a certain minimum value of the porosity is reached. Jensen (1954) puts this critical value of the percentage hole area of a screen at 30-40%; further reductions in penetrability beyond this value decrease the shelter effect only very gradually. It has been estimated that the degree of penetrability of the 2h wide model used in these investigations is less than 26%; therefore, it may be expected that the models, 3h wide and greater, have a penetrability ratio tending gradually from about 20% towards zero. Comparison of the curves for the 2h, 3h, 4h and 5h wide models at elevations of 0.6h and 0.2h reveals that the critical penetrability factor is reached with the 3h model since there is little variation between the curves for that width and those for the 4h and 5h models. The fact that, for widths greater than 5h, the divergence between the curves becomes more prominent implies that, once the critical degree of penetrability has been surpassed, i.e. with barriers less than about 20% penetrable, width of the barrier becomes the limiting factor in determining the extent and nature of the leeward sheltered zone.

An important feature of these results is that, as the model width increases, the eddy zone or the region where reverse currents prevail to leeward of the barrier becomes restricted in extent. This phenomenon suggests that the low pressure area to be expected behind barriers of very low penetrability is eclipsed by the wind flowing over the wide models to a degree dependent upon the width of the model. This supports an earlier theory to the effect that the wind flowing over a wide shelterbelt is drawn down to the ground again very quickly after leaving the leeward edge (Blenk 1952) but is contrary to the suggestion of Nøkkentved (1940) that the wind leaves the leeward edge of a wide plantation more or less horizontally and thereby produces an extended sheltered zone. Field measurements recorded by Nägeli (1953b) behind a coniferous plantation 21.5 heights wide have been plotted in Fig. 26 and show the same general course of the velocity gradient as determined in the wind-tunnel experiments. It is evident that both in the field and tunnel investigations a very marked downward transfer of energy occurs to leeward of wide windbreaks.

The results of these investigations may be summarised as follows:

(a) The width/height ratio in windbreaks has a significant effect in determining the extent and nature of the sheltered zone in their vicinity, although this effect may not be apparent until the critical degree of penetrability (estimated to be about 20%) has been exceeded.

(b) The value of the width/height ratio above which the width of windbreak becomes the limiting factor in determining the shelter effect has been found in these investigations to be 5, although this value may not be expected to have a general application. For example, with windbreaks of more open construction, the critical width/height ratio may be considerably more.

(c) Wide windbreaks appear to lead the wind parallel to their upper surface with a resultant rapid downward transfer of energy after the wind leaves the leeward edge of the windbreak.

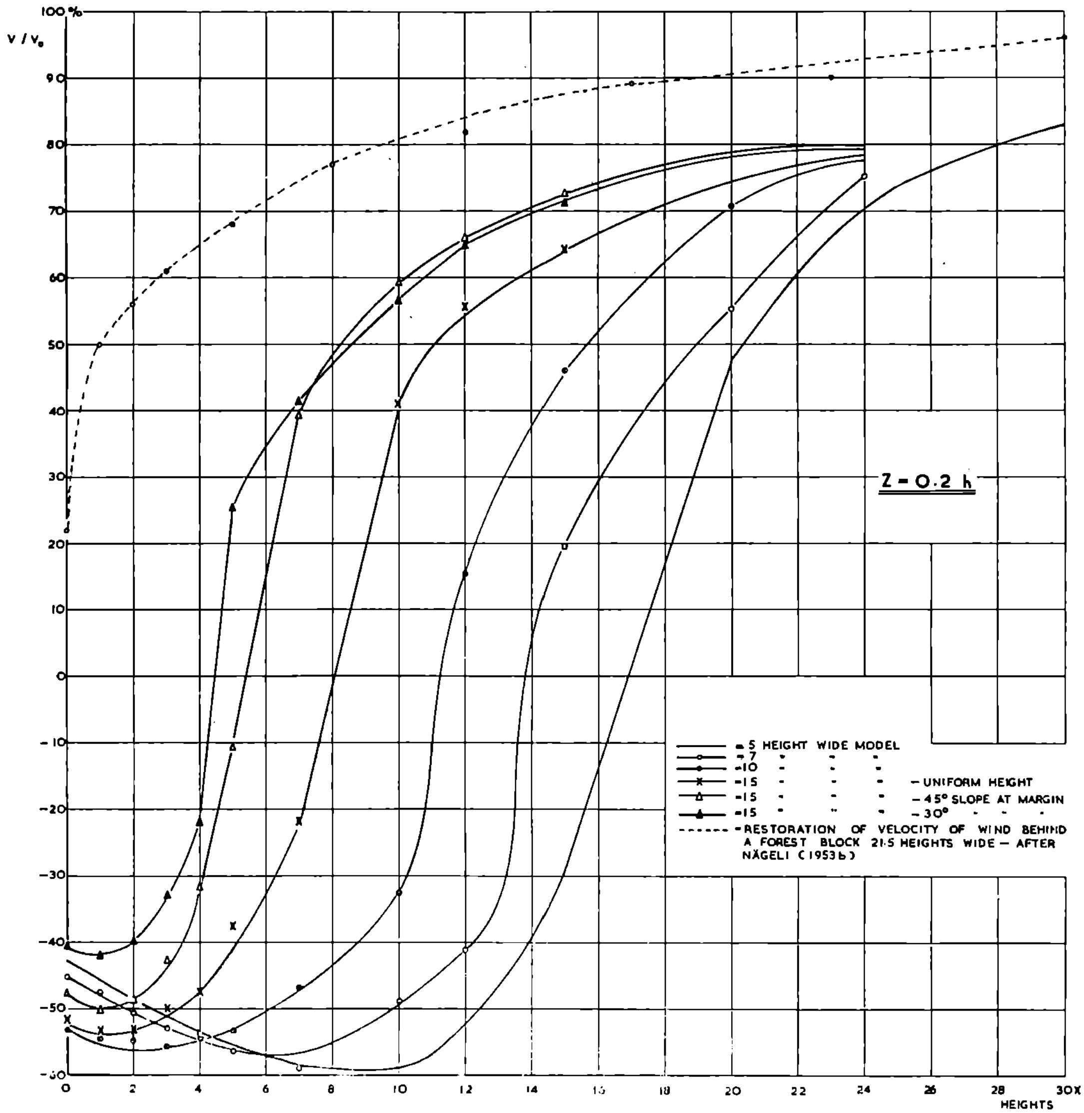


FIGURE 26. Relative wind velocities to leeward of models ranging in width between 5 and 15 times the model-height, illustrating also the effect of the form of the windward edge in the case of three models, 15-heights wide. Measured at 0.2 × the height of the models.

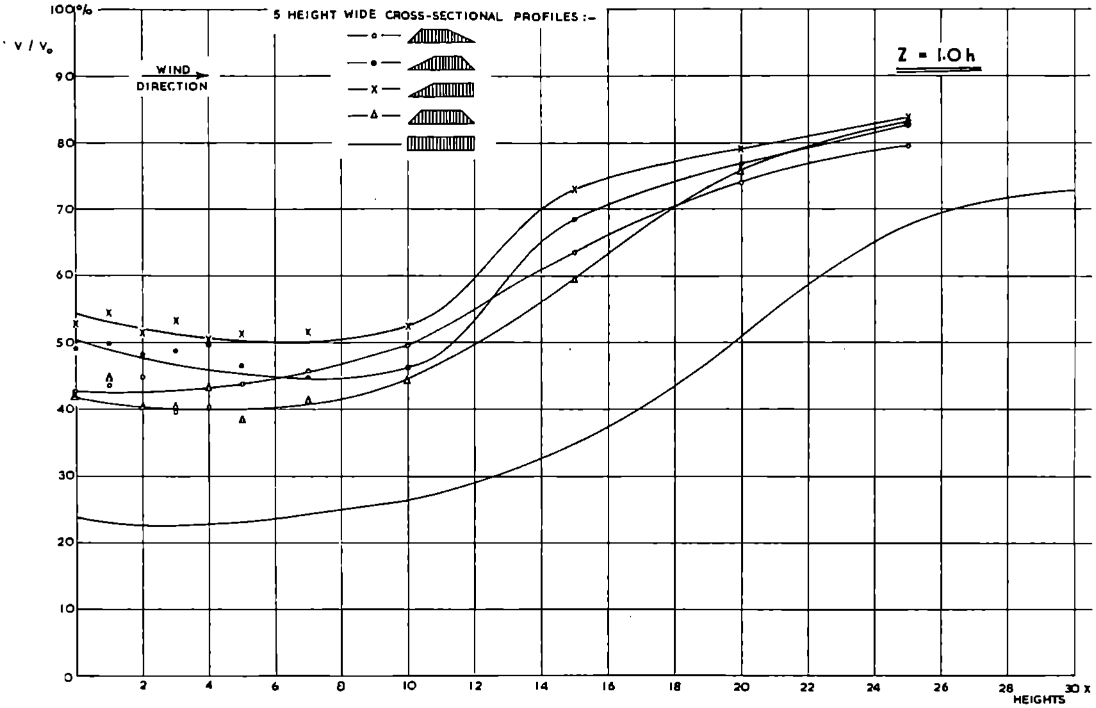


FIGURE 27. Relative wind velocities to leeward of models, 5-heights wide, of varying cross-sectional profile. Measured at the height of the models.

(d) The eddy zone to leeward of wide windbreaks is reduced by the air flow over the top of the model to an extent dependent upon the width of the windbreak (Fig. 39).

(e) This restriction of the eddy zone allows a more rapid resumption of the unobstructed wind velocity with a consequently decreased distance protection to leeward of the windbreak.

The Effect of Shelterbelt Cross-sectional Profile on the Sheltered Area

The investigations of wind velocity relationships to leeward of models of different cross-sectional profiles may be divided into five groups according to the widths of the models employed. The three main groups concern models of widths of 15h, 5h and 3h respectively. In addition studies were made of the 1h wide gradient (45°), the 2h wide gradient (30°) and a model of a natural belt with a gradient of approximately 10°. The results of the investigations are tabulated in Tables 1-6 and illustrated in Figs. 24-36.

(a) Profiles 15 Heights Wide

Three different cross-sectional profiles 15h wide are compared in Figs. 24-26, and are shown diagrammatically in Fig. 20. In the first case the model was of uniform height throughout, thus having a vertical windward edge; in the second case a 45° slope extending over 1h from the windward edge, the remaining 14h width being of uniform height; in the third case a 30° slope extending over 2h from the windward edge, the remaining part of the model being of uniform height.

The results reveal that, in effect, the slope on the windward margin is similar to an increase in the width of the model, the extent of this increase depending upon the angle of the gradient at the windward edge. As the angle of the windward marginal slope becomes more acute higher wind velocities obtain at the height of the model immediately to leeward and the velocity gradient thereafter becomes steeper; at elevations of 0.6 and 0.2h the extent of the eddy zone becomes more restricted, the resumption of velocity more rapid, the degree of shelter less and the distance protection shorter.

(b) Profiles 5 Heights Wide

Five cross-sectional profiles 5h wide are compared in Figs. 27-29. These are shown diagrammatically in Fig. 20 and allotted identification letters.

Regarding the values recorded at 1.0h above the tunnel floor, the scatter found immediately to leeward of the models and extending up to 5h distance illustrates the disturbance in the flow produced by the various windward and leeward marginal slopes but the general trend of the curves can be distinguished readily. These curves show that, at this elevation, none of the designs exhibits the efficiency of the model of uniform height throughout (3E). There is a remarkable similarity between the course of the curves for designs 3B and C and to a lesser extent between A and D, which suggests that the marginal slope at the windward edge of the model has a greater influence on the velocity abatement at this height than leeward slopes. Design A shows a smaller velocity reduction up to a leeward distance of 18h, after which resumption of velocity is less with A than with D; however, for overall effectiveness, design D is obviously preferable.

At 0.6h, the 5h wide model of uniform height throughout (3E) produces a more extensive eddy zone to leeward than the other designs. However, beyond 21h distance there is a pronounced gradient of velocity recovery with this model, which exceeds the corresponding velocity values for design A. For overall effectiveness, however, design E takes precedence. Designs B and C again exhibit a marked

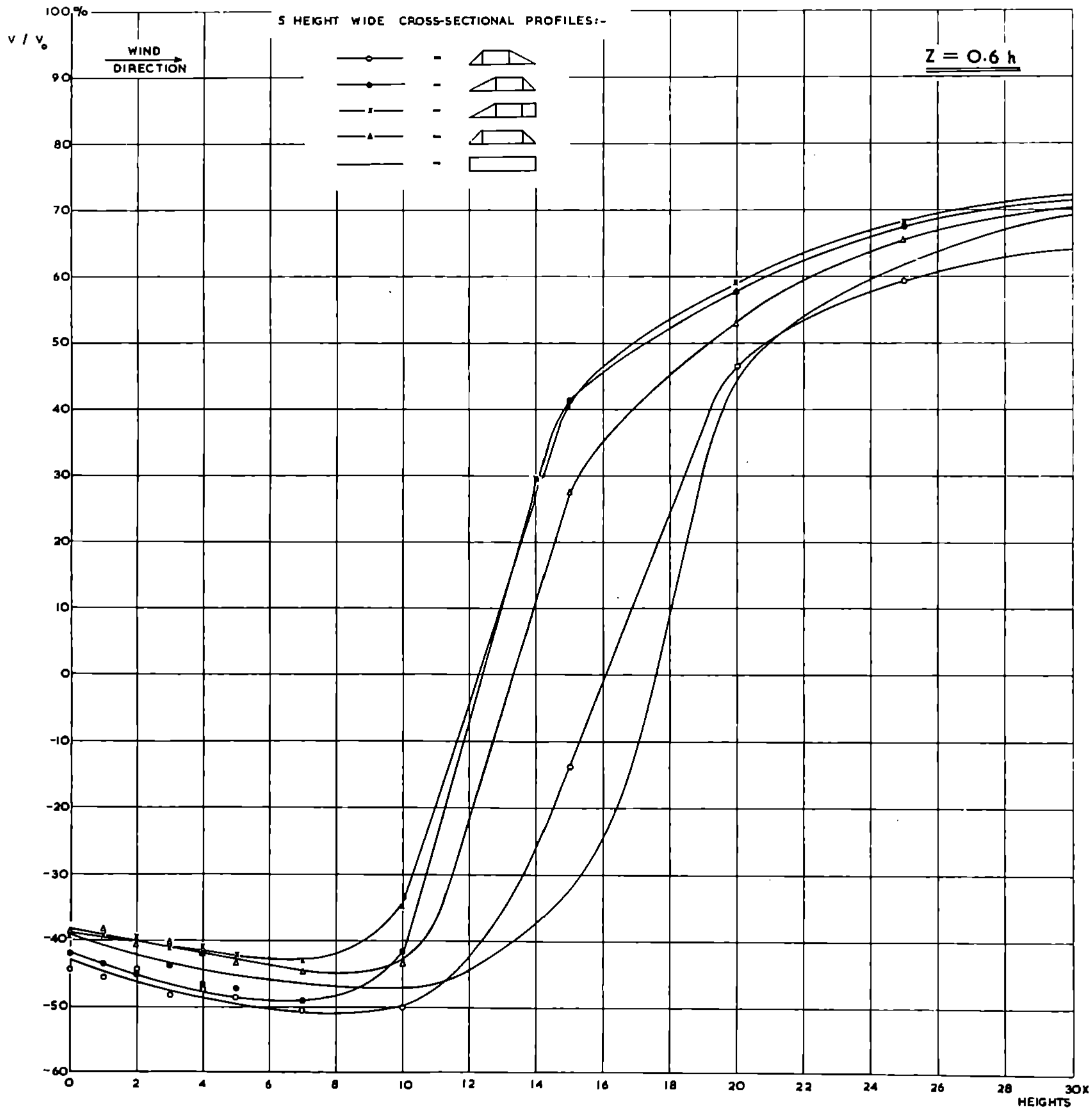


FIGURE 28. Relative wind velocities to leeward of models, 5-heights wide, of varying cross-sectional profile. Measured at 0.6 × the height of the models.

Plate 1. Cup-counter anemometer Mk. II (Meteorological Office).

Plate 2. Air meter or vane anemometer (*left*) and sensitive Type IV anemometer (*right*).

Plate 3. Hastings portable air meter.

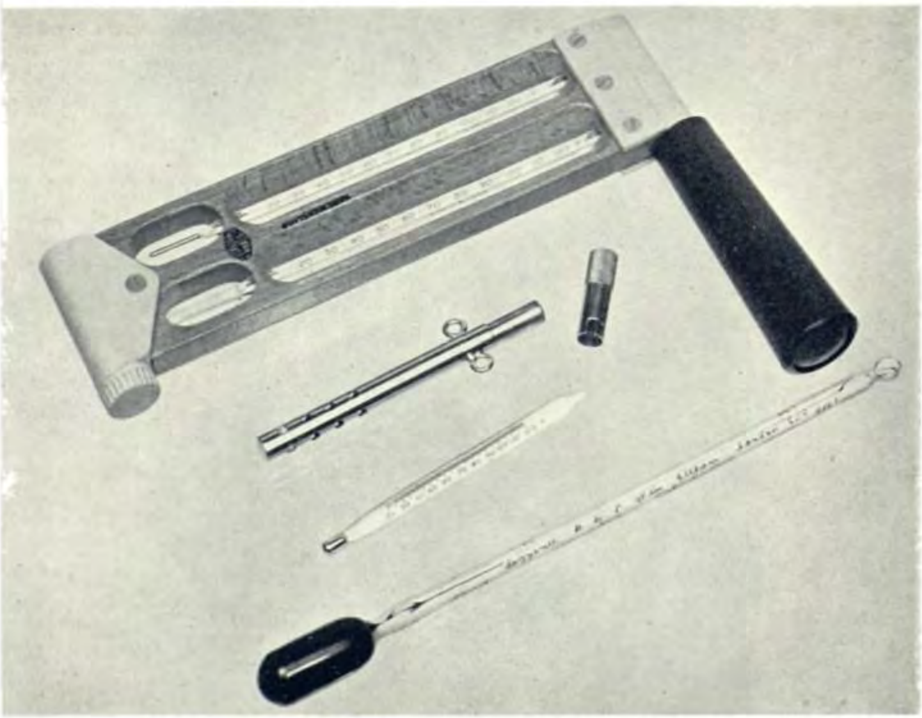


Plate 4. Whirling hygrometer (*top*), Fronde thermometer with case (*centre*) and Kata thermometer (*bottom*).

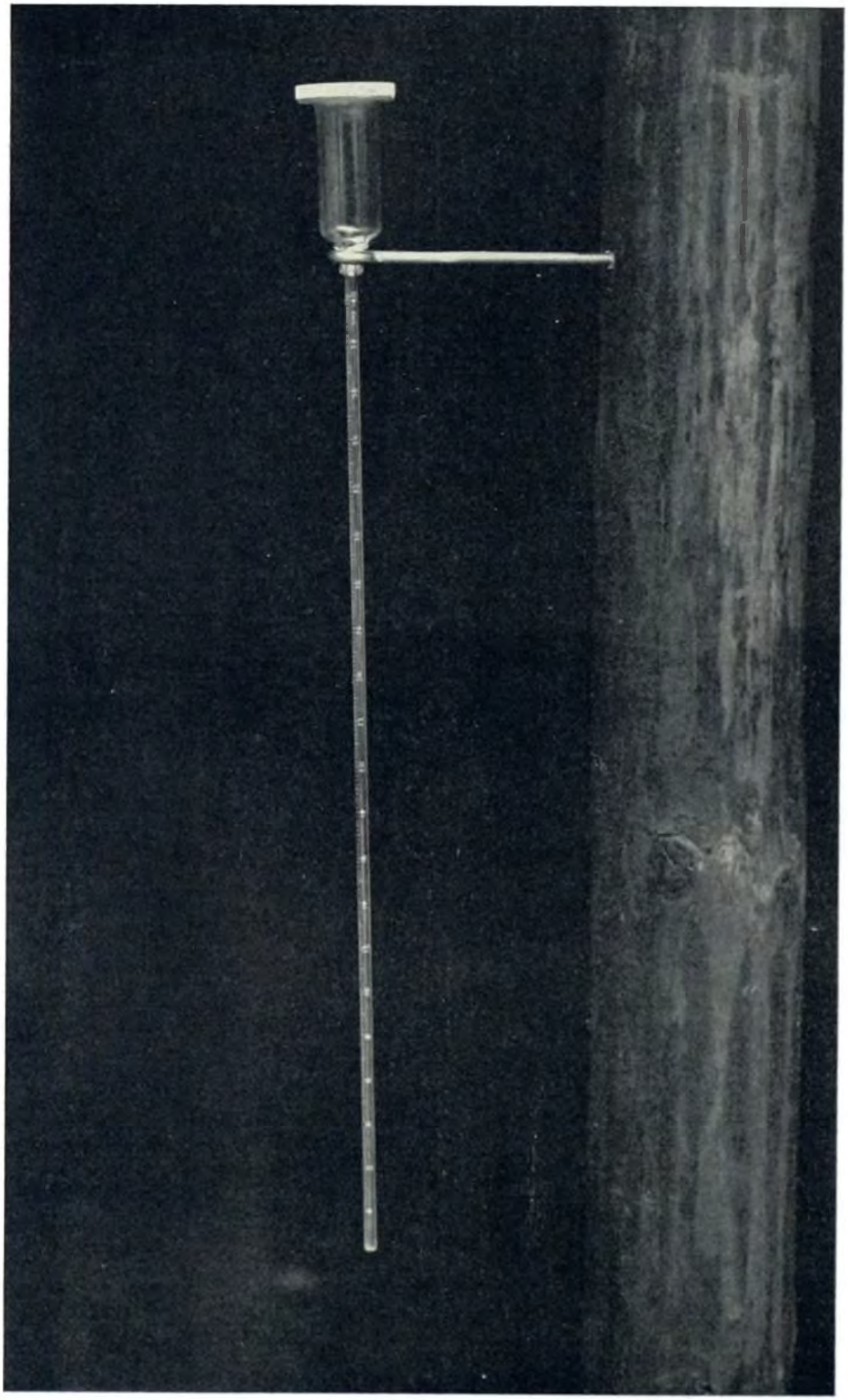


Plate 5. "Thistle" evaporimeter.

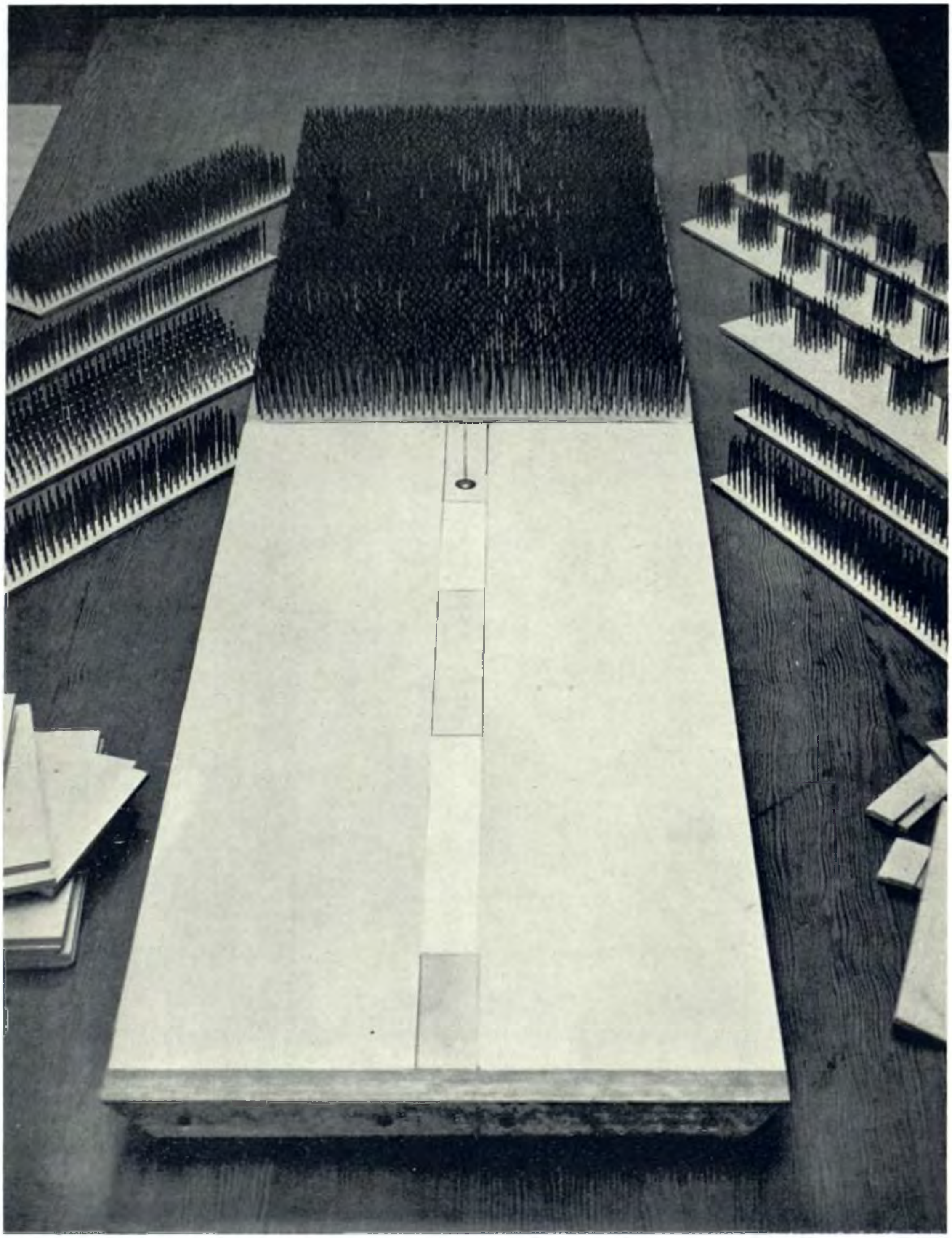


Plate 6. Wind-tunnel base-board, showing the maximum size model in position and the central channel for the pitot apparatus. Further models on either side of the base-board.

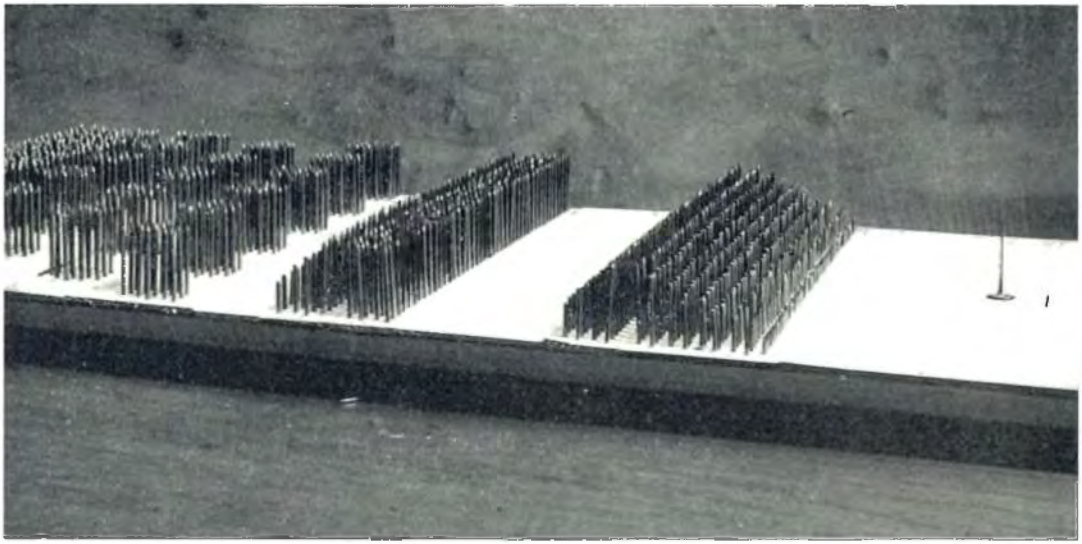


Plate 7. Side-view of the base-board, showing bevelled edge and some of the models.

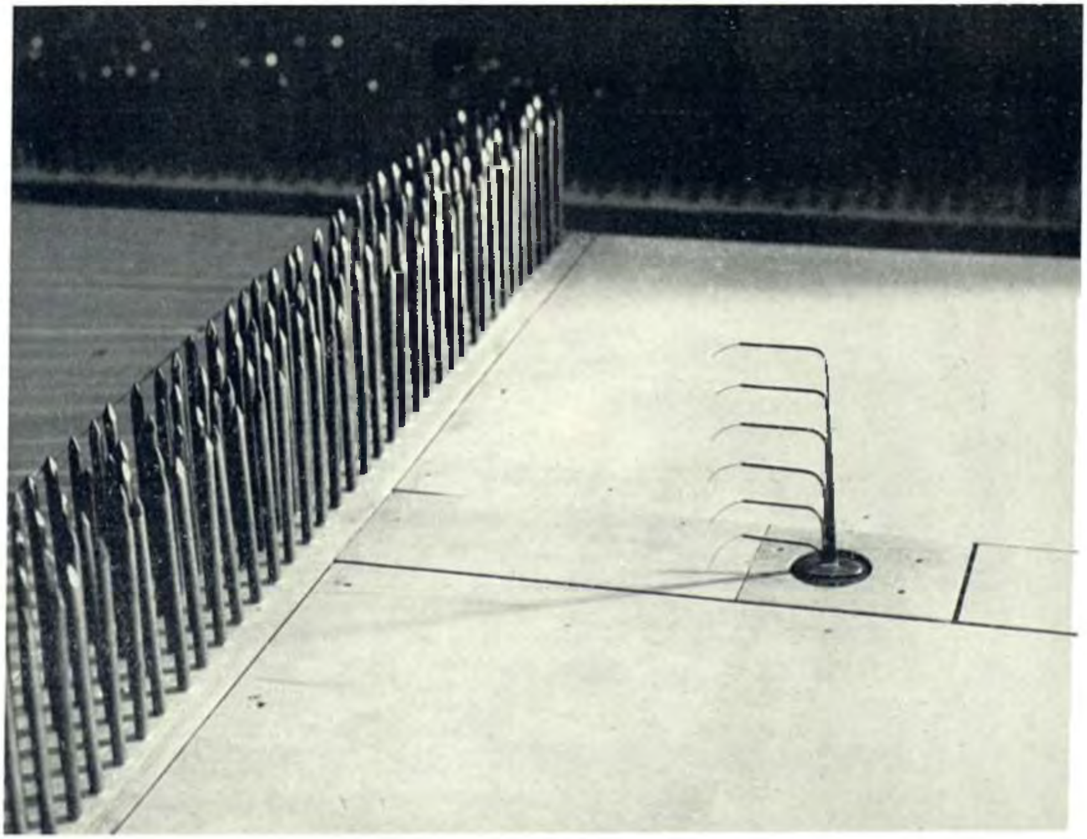


Plate 8. Close-up view of the model, l-height wide, and the pitot apparatus.
(*Note:* Wires protruding from the individual tubes are for protection and identification purposes during erection of the equipment in the wind-tunnel and are removed thereafter.)

Plate 9. The Dreghorn shelterbelt from the north-east, looking towards the Pentland Hills (May 1955).

Plate 10. The Dreghorn shelterbelt, windward margin (July 1955).

Plate 11. The Dreghorn shelterbelt, leeward margin, showing the dry-stone dyke (November 1954).

Plate 12. The Dreghorn shelterbelt, cross-sectional profile, showing the gradation of height from windward (*left of picture*) to leeward, and the windswept character of the crowns of Scots pine (November 1954).

Plate 13. The Currieinn No. 1 shelterbelt, showing the marginal hedgerow of beech and hawthorn (March 1956).

Plate 14. The Currieinn No. 1 shelterbelt, showing the dense interior of unbrashed conifers (March 1956).

Plate 15. Currieinn, showing the marginal hedgerow of beech and hawthorn bordering all belts in the system; in the sixth belt only the hedgerow remains (March 1956).

Plate 16. Shothead No. 1 shelterbelt, showing the structure from the west margin and the scattered hawthorn bushes on the boundary (May 1955).

Plate 17. Shothead No. 2 shelterbelt, showing the open structure of the belt from the west margin (May 1955).

'late 18. The Langwhang shelterbelt, showing the very open condition typical of many old pure conifer shelterbelts on exposed rough grazings throughout the Southern Uplands of Scotland (May 1956).

'late 19. The East Saltoun shelterbelt, showing the windward margin with close hawthorn hedge rarely overhanging the adjoining arable land (June 1955).

Plate 20. The East Saltoun shelterbelt, showing the leeward margin with no hedge but low branching in all species (June 1955).

Plate 21. The East Saltoun shelterbelt, showing an ash group with hawthorn hedge in the background (June 1955).

Plate 22. The Braidwood shelterbelt from the south-west, showing the general configuration of the locality (April 1956).

Plate 23. The Braidwood shelterbelt, showing the western margin and the gradient on which the belt is situated (May 1955).

Plate 24. The Braidwood shelterbelt from the south-east, showing the formation of the glacial drift mound on which the belt is situated and the slope of the ground away from the eastern margin of the belt (April 1956).

ʾlate 25. The Gosford shelterbelt, view north-east, showing the close wind-pruned canopy and the even slope from the height of the wall on the windward margin (July 1955).

ʾlate 26. The Gosford shelterbelt, showing a further section of the belt with a proportion of severely pruned)ines amongst the leaf-tree mixture; the section to the right of the photograph is slightly less severely exposed, owing to a change in direction of the belt (July 1955). Looking south-east.

Plate 27. The Gosford shelterbelt, showing the interior near the leeward margin, which appears rather clos in summer, owing to the low heavy crowns of the old leaf-trees which form an irregular border to the lee sid of the belt (July 1955).

Plate 28. Another view of the Gosford shelterbelt looking north-east.

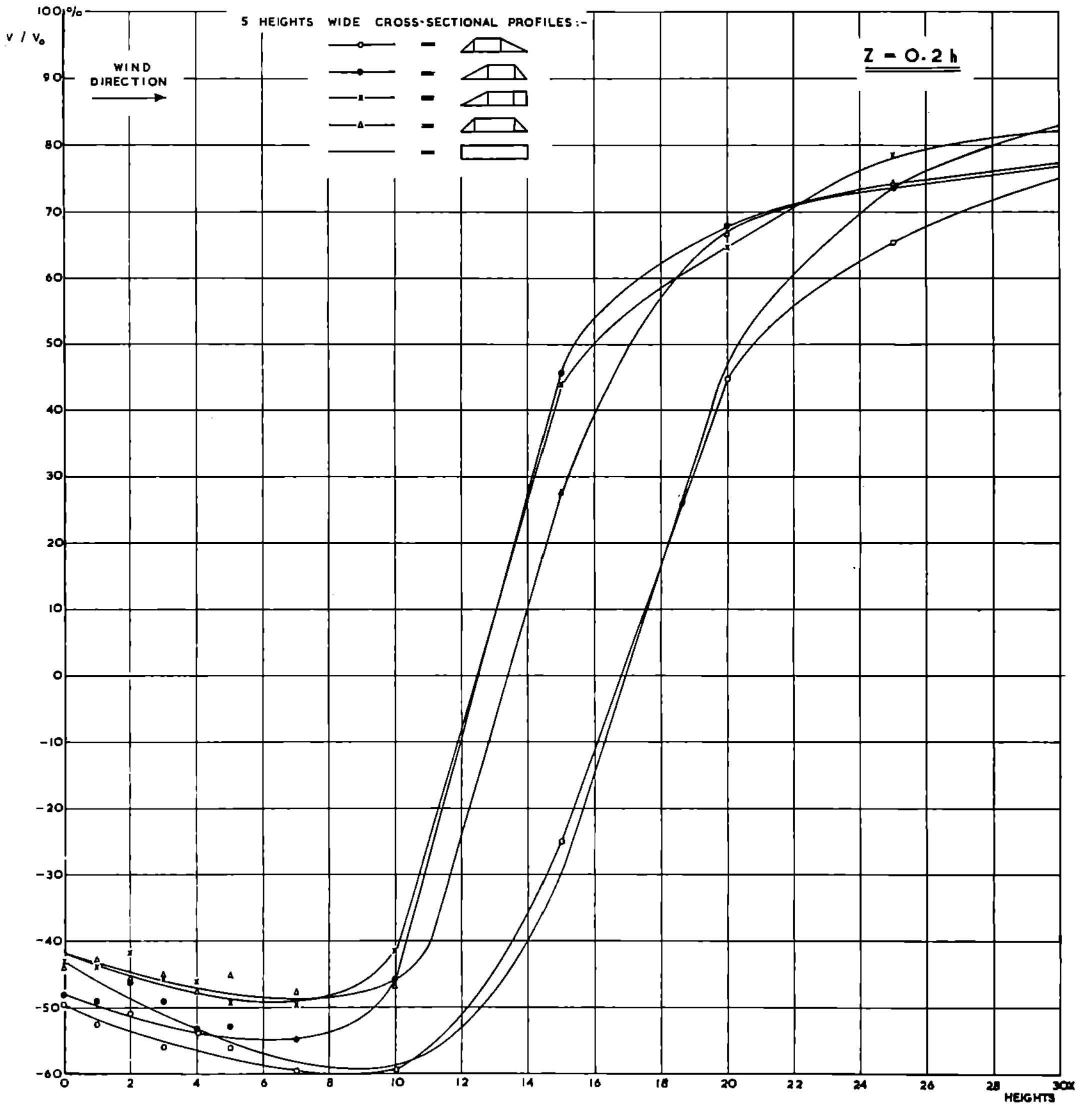


FIGURE 29. Relative wind velocities to leeward of models, 5-heights wide, of varying cross-sectional profile. Measured at 0.2 × the height of the models.

uniformity in their effect, whilst design D ranks third in order of effectiveness.

At 0.2h the pattern is much the same although beyond 20h the differences between the curves for models E and A are more marked, and particularly at 25h. Extrapolation of the graphs beyond 25h would appear to be unreliable owing to the disparity between the course of the curves.

The order of effectiveness of the different designs at the three elevations and the mean for the three elevations is as follows:

1.0*h*	0.6*h*	0.2*h*	*Overall Average*
E	E	A	E
D	A	E	A
A	D	D	D
B	B	B	B
C	C	C	C

Analysing these results, it would appear that the uniform model having a vertical windward margin is more effective at all three elevations on the average than the other designs but at 0.6h is approached very closely by the model A, having a 45° slope at the windward margin and a 30° slope at the leeward edge; at 0.2h this latter design is slightly more effective in distance protection. At all elevations design B is somewhat more efficient than C; both these models have a 30° windward slope and B has a 45° leeward margin whilst C has a vertical edge. It would seem, therefore, that a leeward gradient may be slightly more effective than a vertical edge. This could possibly be explained by the theory that, in the models with a leeward gradient, a small eddy is produced above the slope and acts as a "roller bearing", preventing the downward transfer of energy which occurs with vertical leeward edges in wide models. Further investigations employing a wider range of designs and widths in the models would be necessary to establish this hypothesis. The main evidence to be obtained from these studies is that the designs investigated are not as efficient as the windbreaks having a uniform height throughout and, thus, vertical windward and leeward edges. General principles of fluid dynamics would seem to support this statement, since designs, which, on account of their inclined margins, approach the form of an aerofoil, must tend to cause the minimum disturbance to the air stream and, consequently, produce the minimum shelter effect.

(c) Profiles 3 Heights Wide

Two designs of 3h wide cross-sectional profiles are compared with a 3h wide uniform model in Figs. 30-32. The design with a 45° windward slope and a 30° leeward slope (4A) is the reverse of the second design (4B). The disturbed flow pattern to leeward of the models with inclined margins extends as far as 10h and is illustrated by the scatter of the experimental values (Fig. 30). At the height of the model above the tunnel floor, neither of the designs is as effective as the uniform model (4C). At 0.6h (Fig. 31) positive velocity ratio values occur at the leeward margin due to the flow of air over the top of the models. In the 3h wide uniform model the curve shows a similar tendency but the start of the eddy zone causes the velocity ratio at 0 to be negative in direction. A considerable variation in the extent of the eddy zone produced by designs A and B is to be observed, the former design being much more effective in this respect and exhibiting a more shallow gradient of velocity resumption beyond 20h from the model. At 0.2h (Fig 32) there is less divergence between these two curves as far as 15h to leeward after which point the curve for design B rises much more steeply. Beyond 20h there is a tendency for design A to be more effective than the

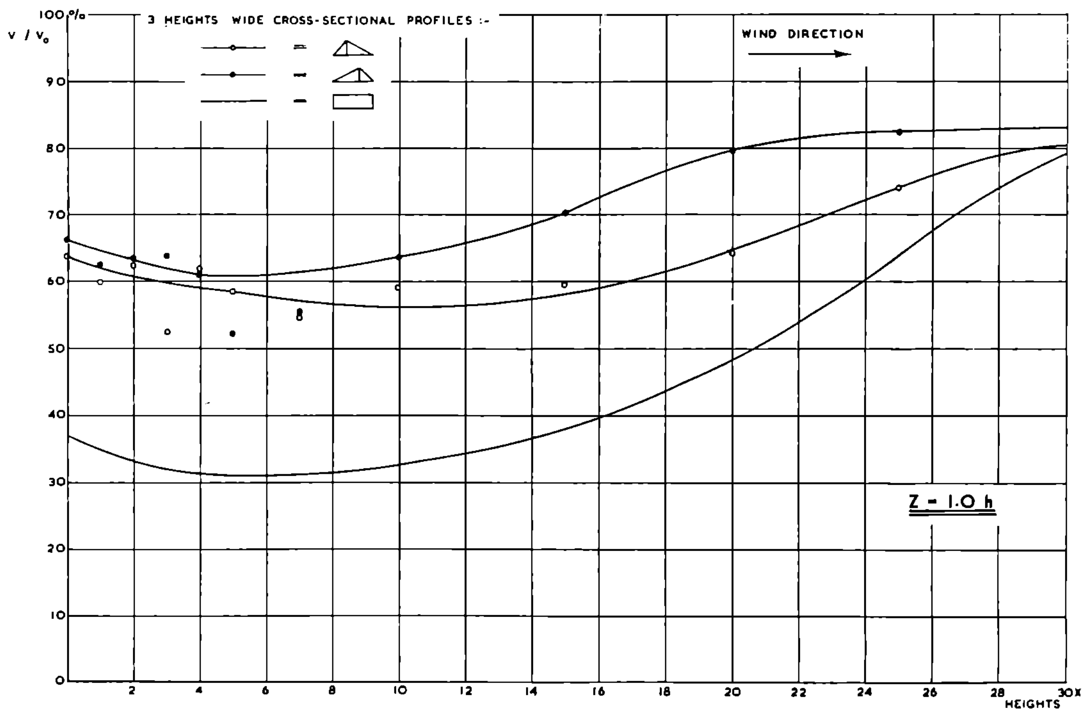


FIGURE 30. Relative wind velocities to leeward of models, 3-heights wide, of varying cross-sectional profile. Measured at the height of the models.

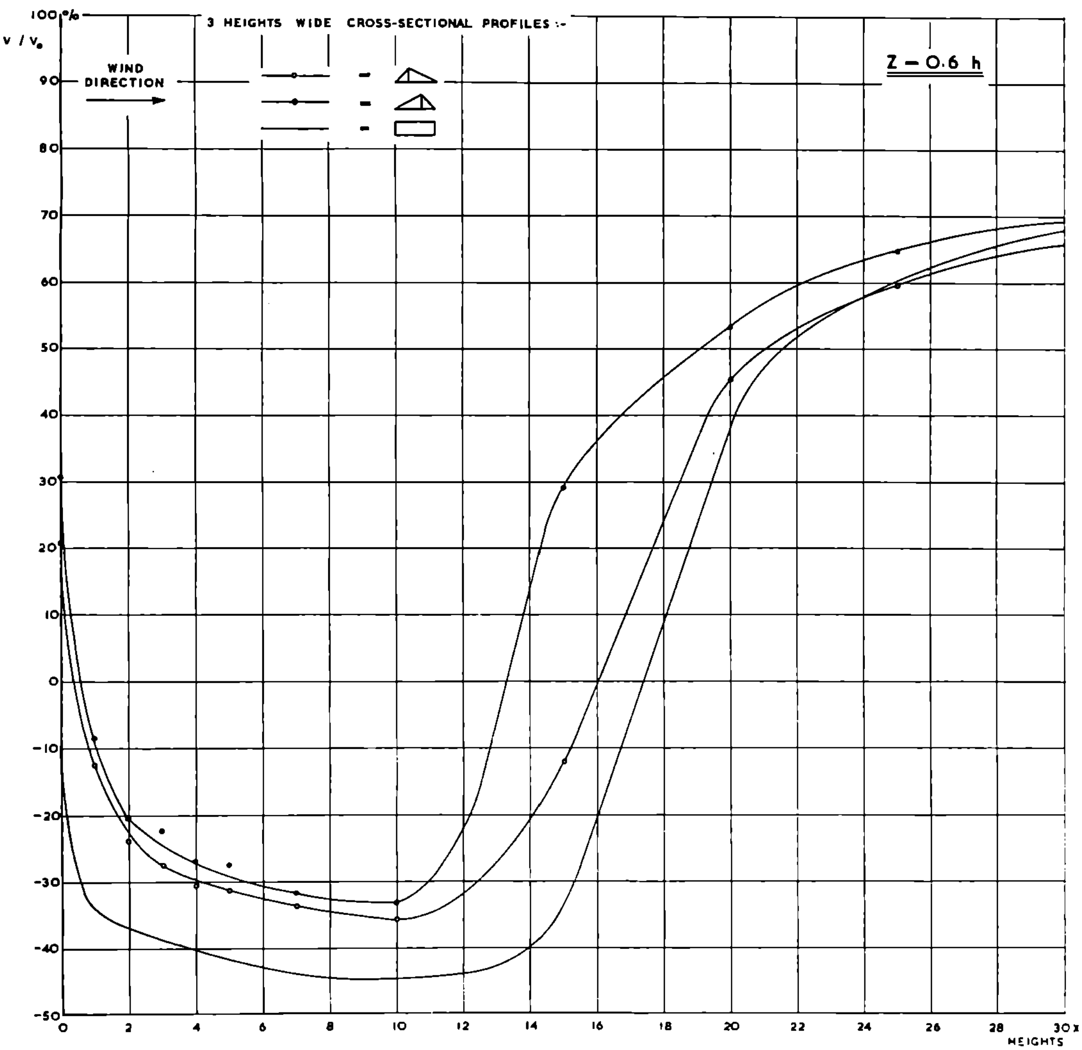


FIGURE 31. Relative wind velocities to leeward of models, 3-heights wide, of varying cross-sectional profile. Measured at 0.6 × the height of the models.

uniform design C, particularly at 0.2h elevation but to a lesser extent at 0.6h also. However, for overall effectiveness the uniform model must be considered preferable.

(d) Profiles 1 Height Wide

In Figs. 33-35 a 1h wide model with a gradient of 45° to windward is compared with a 1h wide model of regular height throughout.

It will be observed that at an elevation of 1.0h (Fig. 33) relative wind speeds to leeward of the 45° model are somewhat higher than in the case of the uniform model, although the curves converge at 30h distant from the model, where 73% of the unobstructed wind speed has been recorded in both instances. After leaving the leeward edge of the inclined model the wind has a relative velocity of 80%, falling very swiftly to 56% at 5h. This phenomenon indicates that, in the sloping design, a larger part of the air stream is deflected over the top of the model and a smaller proportion actually filters through it.

Similarly, at 0.6h (Fig. 34), as far as 15h to leeward of the model considerably higher velocities obtain with the 45° design. After this point the unobstructed velocity is regained somewhat more slowly than in the case of the uniform model and distance protection afforded by the inclined model would appear to be greater. However, this does not compensate for the smaller degree of shelter provided over the first 15h distance behind the model and, for general efficiency, the uniform design must rank first in order.

At an elevation of 0.2h (Fig. 35) it is interesting to note the dispersion of the experimental values for the first 10h distance to leeward of the 45° design. In this region the flow pattern is obviously very disturbed and there is an incipient tendency to formation of an eddy zone with reverse currents immediately behind the model. This zone does not become established definitely however, until 7-10h from the leeward edge of the model. The fact that a negative depression of the horizontal velocity ratio values occurs at all suggests that the slope of the model to windward acts in a manner similar to a reduction in the degree of penetrability, due to the deflection of the major part of the air stream over the top of the model. After the reverse flow zone, which extends as far as 15h down-wind, the velocity gradient is very shallow and between 15h and 30h the shelter effect provided by this model is considerably higher than for the 1h wide uniform model. This implies greater distance protection near the ground to leeward of a 45° windbreak than behind the conventional type with uniform height throughout but the quality of the

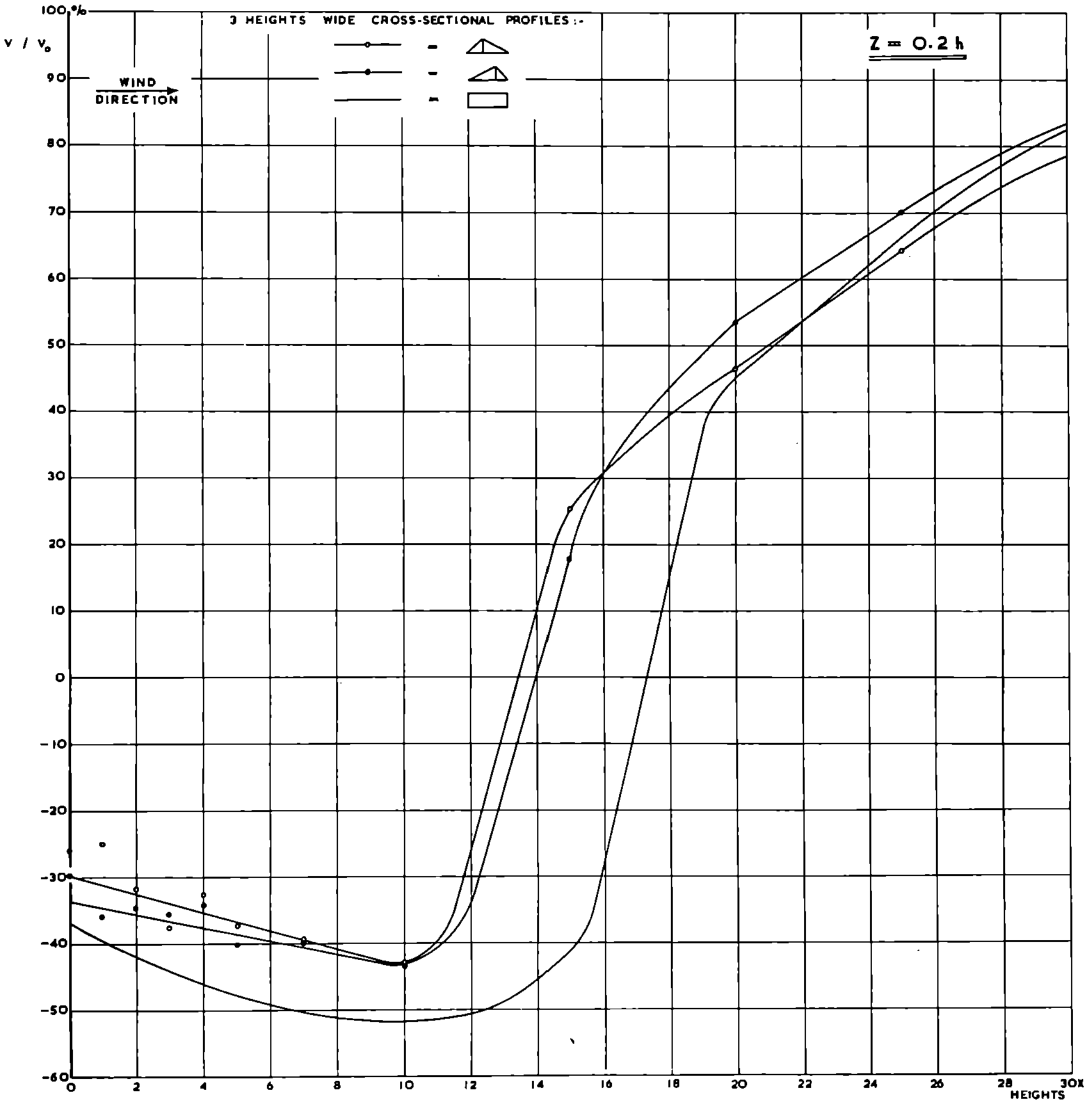


FIGURE 32. Relative wind velocities to leeward of models, 3-heights wide, of varying cross-sectional profile. Measured at 0.2 × the height of the models.

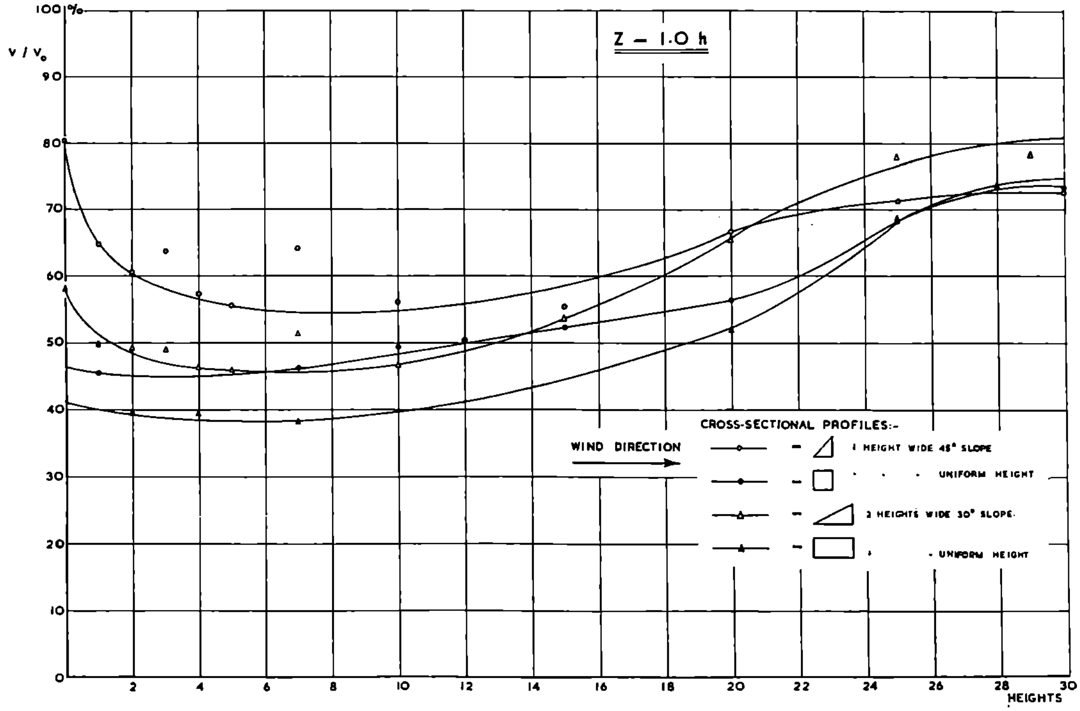


FIGURE 33. Relative wind velocities to leeward of models, 1- and 2-heights wide, of varying cross-sectional profile. Measured at the height of the models.

shelter nearer the windbreak is more effective in the case of the latter design, owing to the zone of intense disturbance produced by the gradient in the former.

For overall efficiency at all three elevations the 1h wide uniform model is therefore superior.

(e) Profiles 2 Heights Wide

A model with a windward slope extending over 2h, corresponding to a 30° gradient, is compared with a 2h wide uniform model and also the 1h profiles in Figs. 33-35.

In the measurements recorded at the height of the model (Fig. 33) the relative velocities immediately to leeward of the sloping model are somewhat higher than in the case of the uniform model with its horizontal upper surface but the differences are less than beteen the corresponding 1h wide profiles. Both the 2h model curves follow the same general course, with a moderate gradient of velocity resumption, but the shelter effect throughout the leeward measurement line is much lower than in the case of the 30° design.

At 0.6h (Fig. 34) the wind speeds measured immediately behind the 30° model are very high, ranging from 99% at the leeward edge to 3% at 5h, due no doubt, as in the case of the 1h 45° model, to the compression of the streamlines as the air stream is deflected over the model and the consequent "jetting" of the air through the upper spaces of the rearmost rows of nails used in the manufacture of the models. Because of this the eddy zone is not established until 6h leeward of the model, as compared with a corresponding zone extending from the leeward edge in the case of the uniform model. The magnitude of the negative depression of the velocity ratio values is also considerably smaller and the eddy zone is terminated somewhat earlier than with the 2h wide model. After this point the resumption of the unobstructed velocity occurs very quickly with the inclined model.

Similar conditions obtain at 0.2h above the tunnel floor (Fig. 35), although here the eddy zone becomes established at 1h downwind from the 30° model. It extends only as far as 14h, compared with about 18h in the case of the uniform model, and from 15h to 30h the unobstructed velocity is regained very rapidly. At all elevations, therefore, the model with a 30° windward gradient is appreciably less effective than the 2h wide uniform design. It is also much less efficient as regards distance protection than the 1h wide model with a 45° windward gradient.

(f) Model of the Gosford Shelterbelt

Measurements of wind velocity condition downwind from a 4h wide scale model of the Gosford Shelterbelt were conducted for subsequent comparison with data from field investigations. The different construction of this model in relation to that of the models used in the previous studies of cross-sectional profiles precludes accurate qualitative comparison of the windward slope in this particular model with the 45° and 30° gradients of the earlier experiments. However, certain features of the results shown in Fig. 36 are of interest when assessing the influences of different shelterbelt cross-sectional profiles on the sheltered areas in their vicinity.

In this model, the gradient of the windward slope is 10° 18′ but the even slope does not continue to ground level at the windward edge, owing to the presence of a stone wall in the natural belt; this has been represented by a vertical solid plate 1.375 cm in height. The inclined surface rises uniformly from the top of this plate to a maximum height of 5 cm (1h) at the leeward edge.

The horizontal velocity ratios recorded at the height of the model show that the wind speeds immediately to leeward of the model are considerably higher than in the case of the 15h wide profiles, which results they resemble most closely in the general trend of the curves. The restoration of the unobstructed velocity field also occurs more rapidly and there is a smooth rise from 63% at 7h to 91% at 25h.

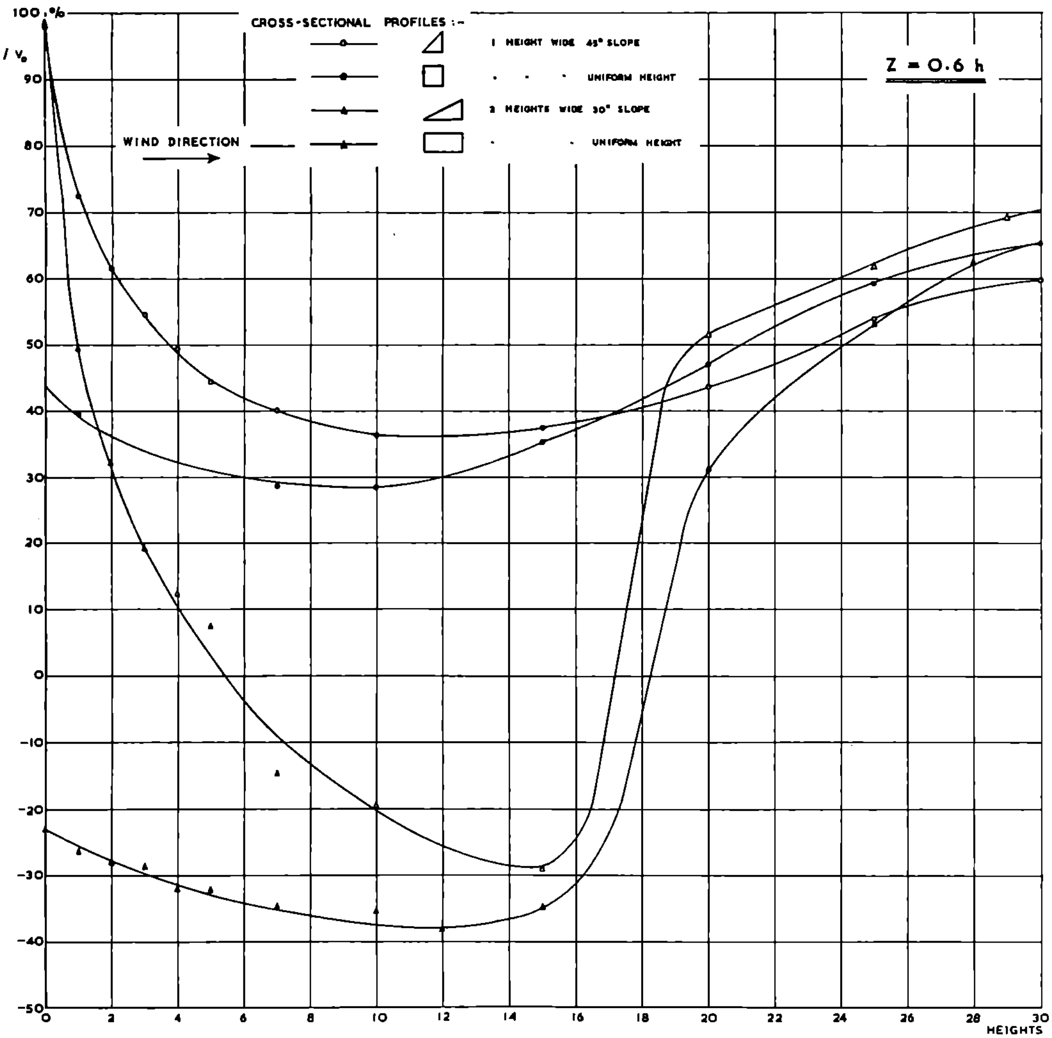


FIGURE 34. Relative wind velocities to leeward of models, 1- and 2-heights wide, of varying cross-sectional profile. Measured at 0.6 × the height of the models.

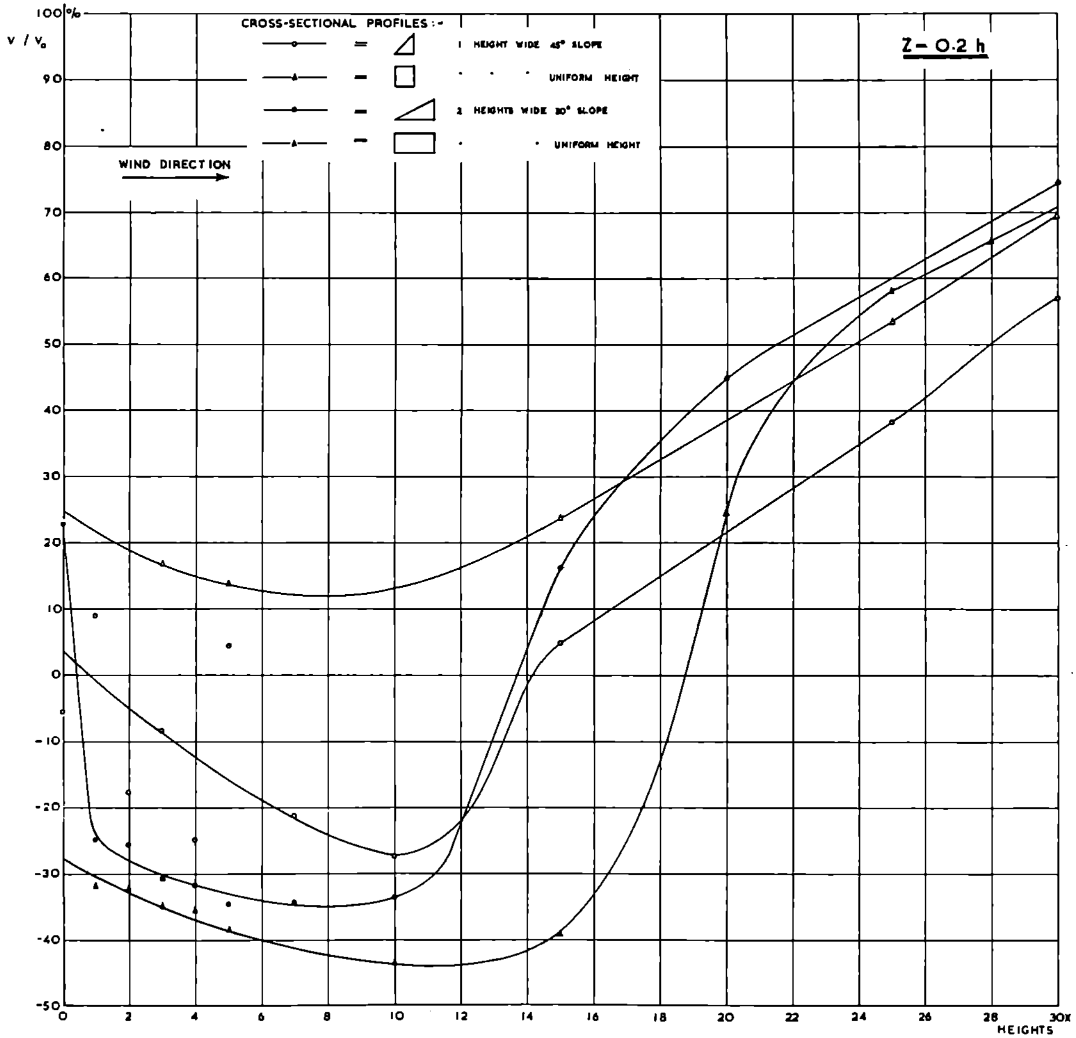


FIGURE 35. Relative wind velocities to leeward of models, 1- and 2-heights wide, of varying cross-sectional profile. Measured at 0.2 × the height of the models.

At an elevation of 0.6h the results reveal a very restricted zone of reverse currents, extending from the leeward margin of the model to 5-6h. At 7h down-wind from the barrier the wind has already attained 48% of its unobstructed velocity and the curve rises evenly from this point to 81% at 25h.

At 0.2h the eddy zone extends to slightly more than 6h from the leeward edge but a relative wind speed of 23% is recorded at 7h, after which the curve rises very steeply to 94% at 25h.

The relative velocity values recorded for the 10-25h horizontal range down-wind from the model are somewhat higher at 0.2h than at 0.6h above the tunnel floor and, for two points, exceed the values at an elevation of 1.0h. This does not imply that the absolute velocities at 0.2h are higher than at the other elevations; in fact, the reverse is the case. In the horizontal velocity ratios the observed value at a point along the test section of the tunnel is related to the unobstructed velocity at this same point, i.e. at the same horizontal distance and the same height of measurement. The higher percentage velocity values constantly obtained towards the end of the measurement line at this elevation throughout the series of experiments may be attributed to the fact that, in the unobstructed tunnel, wind speeds showed a less gradual diminution at 0.2h above the floor, presumably due to the development of the boundary layer; the presence of a model in the tunnel may be supposed to have interfered with this boundary layer development and lessened the gap between the observed and standard velocity readings.

It is clear that the shelter effect exhibited by the model of the Gosford belt is therefore very slight at all elevations and considerably less than the shelter found behind the 15h wide models described earlier. Owing to the acuteness of the gradient and the almost impermeable construction of the model, this was to be expected from the results of the earlier studies. These particular results will be referred to later in connexion with the field investigations of the natural belt.

Conclusions to be drawn from these wind-tunnel investigations of the effect of various cross-sectional profiles in windbreaks may be summarised as follows:

(a) In effect, a gradient on the windward margin of a wide windbreak is similar to an increase in the width and restricts the extent of the sheltered zone accordingly to a degree dependent upon the acuteness of the angle of this gradient.

(b) An inclined windward edge causes deflection of the major part of the air stream over the top of

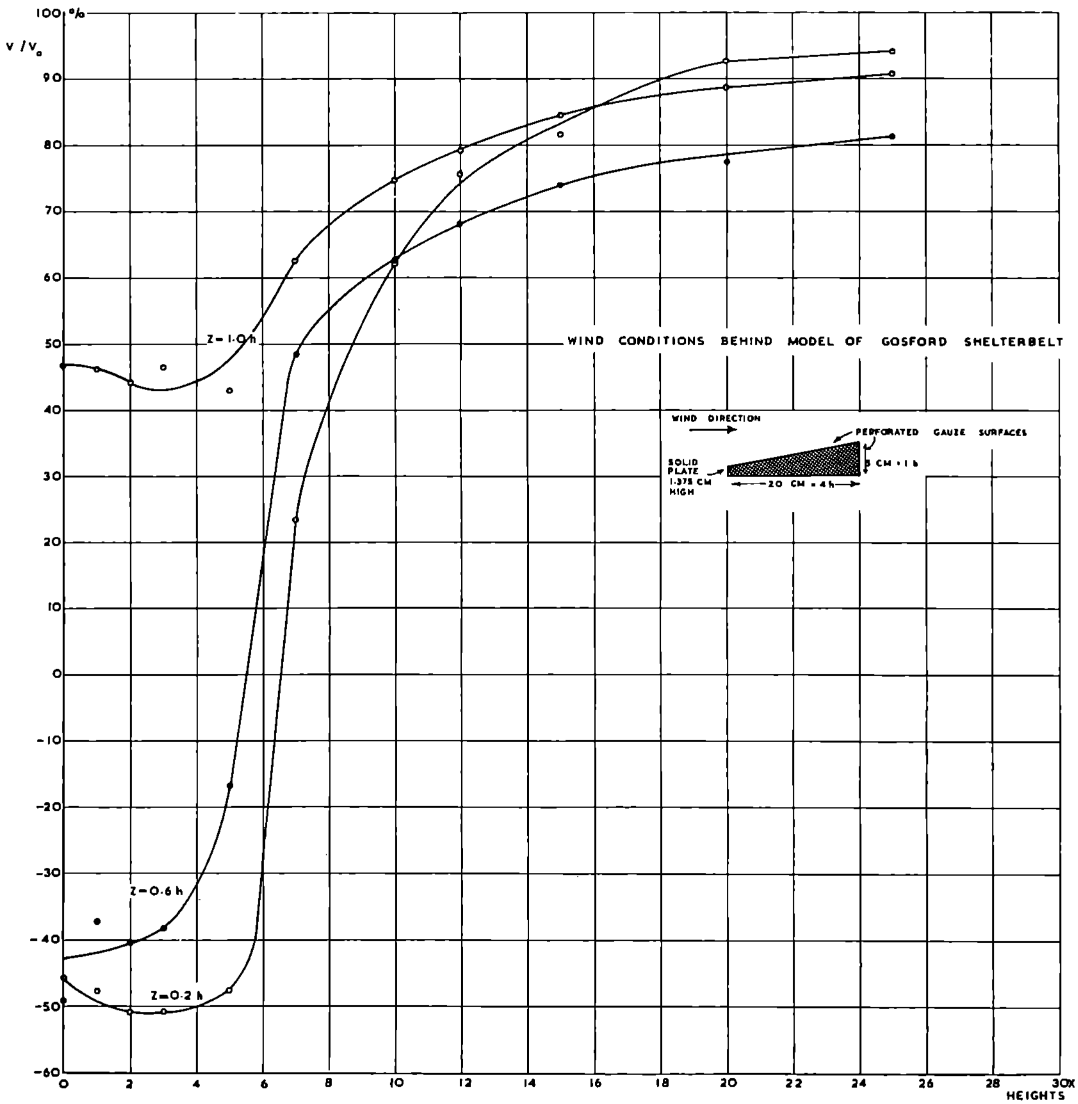


FIGURE 36. Relative wind velocities to leeward of the model of the Gosford shelterbelt, measured at 1.0, 0.6 and 0.2 times the height of the model (see also Fig. 50).

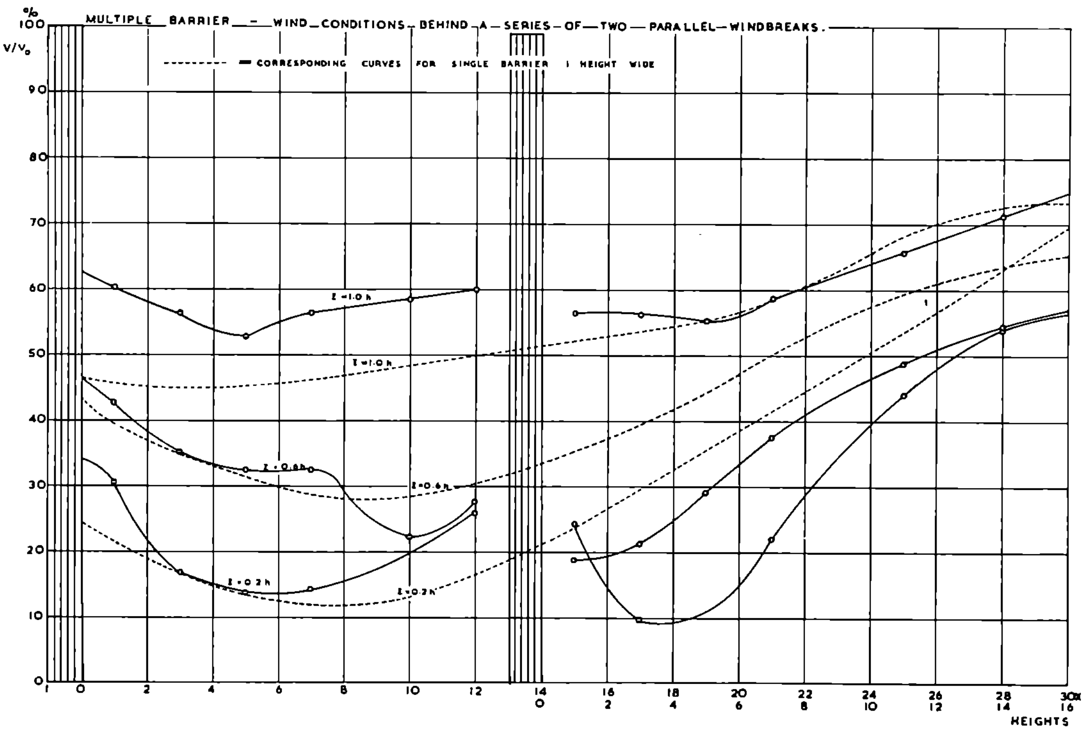


FIGURE 37. Relative wind velocities in the vicinity of a series of two parallel model windbreaks, each 1-height in width and separated by a distance of 13 times the model-height. Measured at 1.0, 0.6 and 0.2 times the height of the model.

the model, thus reducing the effective degree of penetrability of the windbreak; the more shallow the gradient, the more pronounced is this upward deflection of the stream.

(c) Windbreaks with vertical windward and leeward edges are generally more effective in reducing wind velocity than designs with various combinations of windward and leeward gradients and particularly so at the height of the windbreak above ground.

The Effect of a System of Two Parallel Windbreaks on the Sheltered Area

For the purpose of this investigation two similar models, each 1h wide and of uniform nail height throughout, were erected parallel to one another and separated by a distance of 13h. This arrangement restricted the measurement range down-wind of the rearmost model to 14h (equal to 28h behind the first screen) but wind speeds were observed also between the two barriers. The results are compared with those obtained with a single model, located at the same position as the up-wind barrier, in Fig. 37.

It will be observed that at the height of the models the minimum velocity occurs at 5h to leeward of the first model, after which there is a gradual increase in the wind speed as far as 1h to windward of the second barrier. Between the two barriers higher velocities were recorded at this elevation than were found to occur behind the single screen; the significance of this is not fully understood but is probably due to a difference in pressure developed between the two models, although the divergence between the curves for the multiple barrier and the single screen is quite different at the other elevations. Behind the second model there is a slight fall in the curve immediately to leeward but after 5h down-wind from this second barrier the curve corresponds very closely with that for the single barrier, indicating that, at this elevation, there is no cumulative shelter effect produced by the parallel screens and no extended distance protection.

At 0.6h above the floor, the velocities measured behind the first model are similar to those found behind the single model as far as 5h to leeward. After this point it would appear that the development of a high pressure area in front of the second barrier causes a depression in the curve, although a sharp rise in the curve occurs as the wind approaches the edge of the second screen. At 1h behind the rearmost model there is a slight decrease in velocity, which at this point is 19% compared with 36%

when only the first screen is in position. From here the curve rises smoothly and its course is almost parallel to that of the single barrier. At 30h to leeward of the latter the recorded velocity was 65%; at the same point with the two models in position, i.e. 16h leeward of the second model, the corresponding value obtained by extrapolation of the curve is 57%. At this elevation a cumulative effect, though small, can be discerned.

The measurements at 0.2h show a depression of the curve to 14% at 5h behind the up-wind model, the same as recorded behind the single barrier. The curve then rises more rapidly in this instance than with the single screen and there is no further decrease in velocity in front of the second model as found at 0.6h. Leeward of the second barrier the curve falls to a minimum velocity of 10% at 3-4h, compared with a speed of 30-32% at the same points behind a single screen. After this point the curve rises steeply, following the same general pattern as the single model curve but attaining only 56% at 16h downwind of the rearmost model (i.e. 30h to leeward of the first barrier) corresponding to 69% in the case of the single model. Thus, there is a pronounced cumulative effect of shelter near the ground with the two parallel screens although the gradual convergence of the curves illustrates that this would disappear further down-wind.

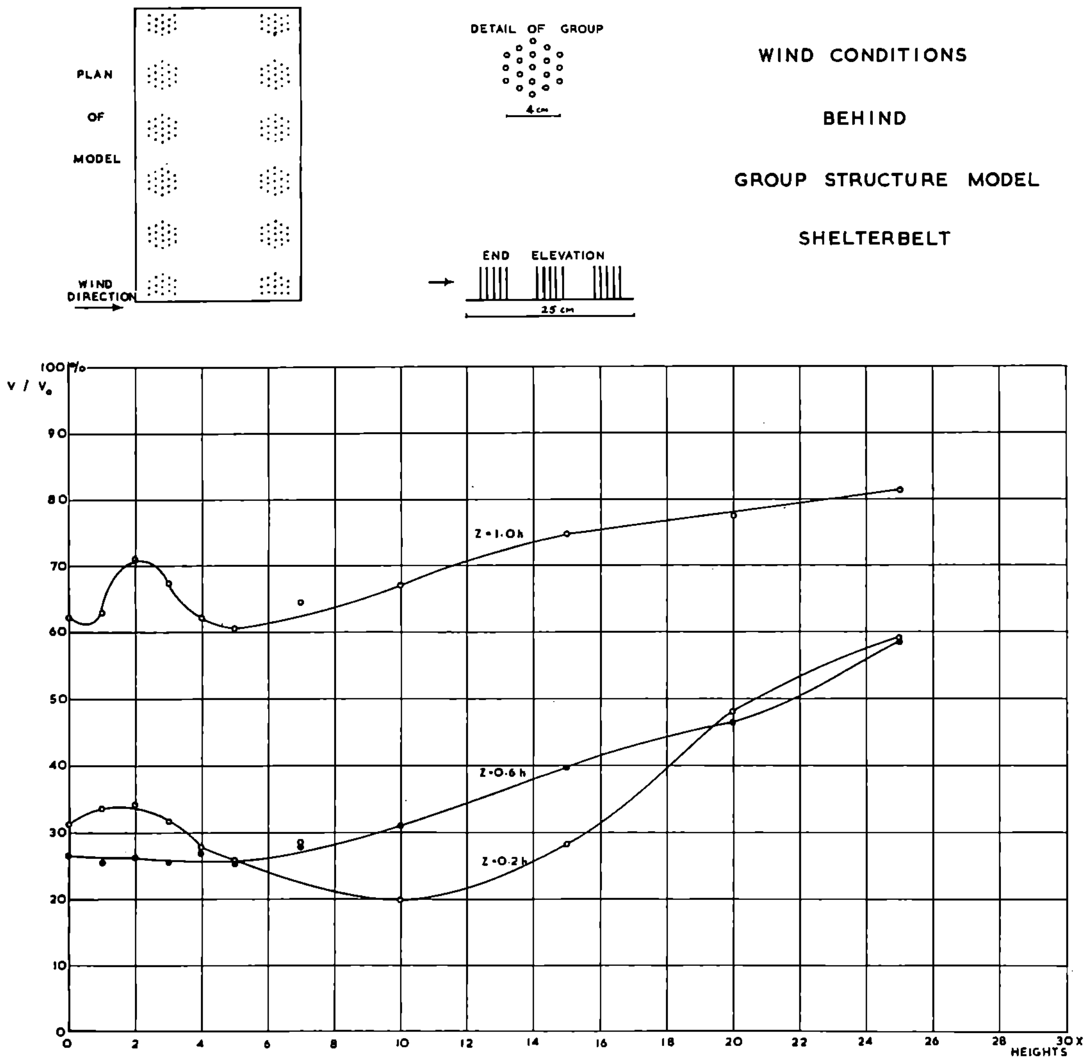


FIGURE 38. Relative wind velocities to leeward of a model, consisting of a series of groups. Measured at 1.0, 0.6 and 0.2 times the height of the model.

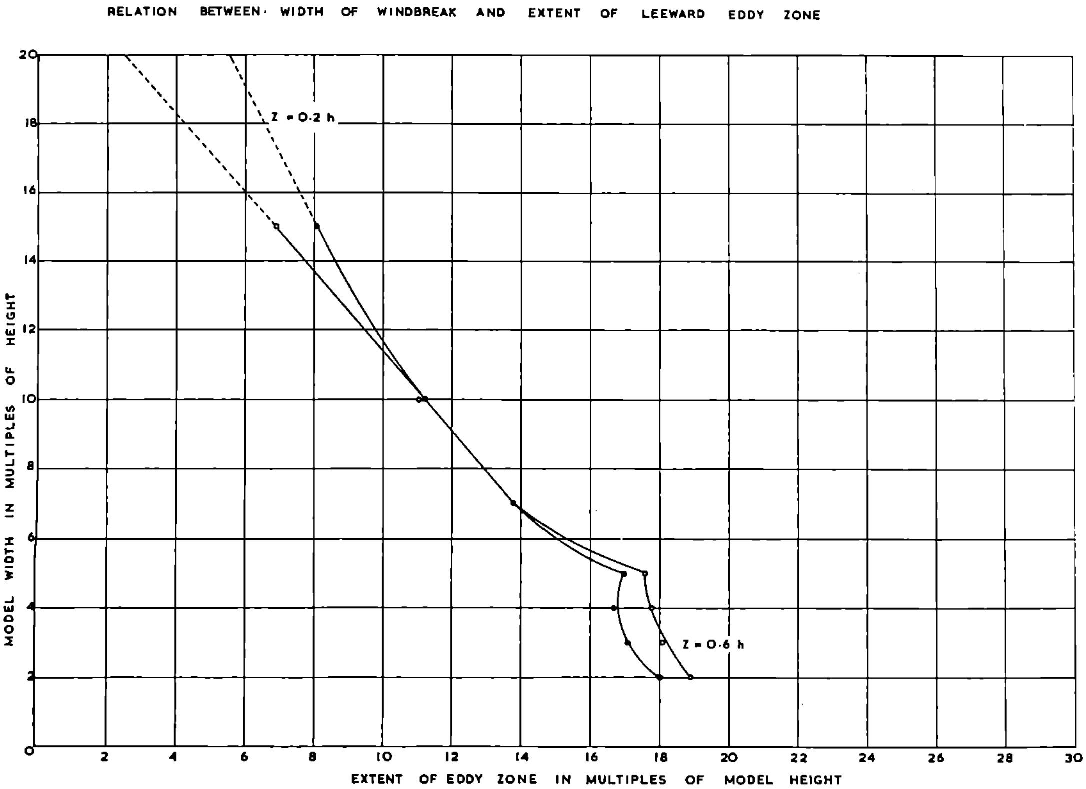


FIGURE 39. The relation between the width of the model windbreaks and the extent of the leeward eddy zone, from velocity measurements at 0.6 and 0.2 × the model-height above the tunnel floor.

It may be concluded from these results that, at a spacing of 13 times their common height between a system of two parallel windbreaks, the shelter effect to leeward of the rearmost screen is somewhat greater than behind a single screen at 0.6h and 0.2h elevation above the datum and is more pronounced near the ground; at the height of the windbreaks no cumulative effect is to be detected. This cumulative effect near the ground extends to at least 16h down-wind from the rearmost barrier but shows a tendency to disappear entirely further down-wind.

The Effect of a Group Structure Windbreak on the Sheltered Area

The results of wind velocity observations to leeward of a 5h wide model comprising a spaced-group arrangement, instead of the conventional uniform spacing of nails employed in the other models, are shown in Fig. 38, together with a plan and elevation of the model design. A standard height of the groups was used throughout, so that the model resembled a series of " penetrable cylinders" arranged in three rows.

The curve in respect of the measurements at an elevation of 1.0h shows higher velocities than obtained behind a 1h wide uniform model throughout the range of the observations with a characteristic, abrupt rise between 1-5h behind the model, due to the jetting of air between the groups.

At 0.6h above the tunnel floor there is a marked improvement in the shelter effect, which is superior to that provided by the 1h uniform model as far as 7h down-wind of the model, after which the curves correspond fairly closely.

At an elevation of 0.2h the shelter effect is not as high as that obtained behind a 1h wide uniform model and relatively high velocities are found over the first 5h distance to leeward of the group model, probably attributable to draughts between groups. However, a minimum velocity of 20% is observed at 10h down-wind of the barrier, corresponding to a minimum of 12% at 7h, rising to 13% at 10h, with the 1h wide model. Beyond this point the curves for the two models follow the same general trend with somewhat higher relative velocities recorded with the group structure model.

These results demonstrate that the group model is slightly inferior in protective efficiency to the 1h wide uniform design, to which it must correspond most nearly in its degree of penetrability to the wind. It is also somewhat less effective, at an elevation of 1.0h, than the 5h wide uniform model, to which it corresponds in overall width; at 0.6h the average shelter effect of these two designs is similar between 20 and 25h down-wind of the models, although the trend of the curve for the group design suggests that the unobstructed velocity of the wind will be restored more rapidly further leeward of the group structure; at 0.2h the group model is more effective as regards distance protection, than the 5h wide uniform model, comparing the respective wind speeds of 59% and 74% recorded at 25h down-wind. An important feature of the group model is that no reverse flow conditions are produced at any elevation. Consequently, it may be more efficient with regard to the quality of the shelter than the uniform model of the same overall width and, for this reason, may warrant more detailed investigation in field studies.

Conclusions to be drawn from the wind-tunnel studies of windbreaks will be discussed in relation to their practical application in a later chapter.

Chapter 10

FIELD INVESTIGATIONS OF MICROCLIMATE IN THE VICINITY OF SHELTERBELTS

FIELD STUDIES of microclimatic factors, particularly wind velocity, were undertaken in the vicinity of selected shelterbelts during the period 1953-55 with the immediate purpose of assessing the efficiency of the particular belt structures involved and, ultimately, of deriving detailed prescriptions of the optimum structures. In this connexion, the term "structure" as applied to the shelterbelt comprises the composition not only by species but also by espacement of the trees and shrubs, their height, stage of development and general condition.

The field investigations consisted of short-term comparative observations of microclimatic factors in the sheltered areas when general weather conditions proved favourable for such studies. Continuous observation of any physical factor over longer periods was not attempted in this programme.

Experimental work was restricted to some extent by meteorological and ground conditions. As far as possible, investigations were conducted only when a wind direction more or less normal to the axis of the shelterbelt under observation prevailed, i.e. when the belt was displaying maximum efficiency, and when the wind was reasonably constant so that strong gusts alternating with periods of near-calm were absent. The latter consideration was important in view of the experimental procedure adopted. On several occasions observations had to be discontinued because of sudden changes in wind direction, calm periods and thunderstorms, the latter especially during the summer months. Further limitations were imposed by the situation of many belts on irregular ground, where comparative data obtained could not be attributed entirely to the influence of the shelterbelts. Within certain shelterbelt systems, as found on the Pentland Hills and elsewhere, it was frequently impossible to obtain standards for comparison with the microclimatic data of the sheltered area, e.g. a value of the wind velocity which could be expressed accurately as the "free" or "unobstructed" velocity for that region. In other cases, the presence of buildings and other obstacles up-wind of the shelterbelt prevented exact study of the belt influences. Gaps caused by wind damage in some belts interfered with the laying-out of a suitable measurement line. Similarly, field crops adjacent to belts curtailed observations in many instances during the growing season, when it would have been impracticable or unreasonable to have carried out the investigations. Availability of equipment, transport and field assistance contributed additional restrictions in the execution of the field work.

Procedure

(i) Wind Conditions

Owing to the trial of different types of anemometer and the frequent delay in obtaining delivery from the manufacturers, instrumentation and experimental technique regarding field investigation of wind conditions in the vicinity of shelterbelts were not standardsied until April 1954. In early 1953 vane anemometers had been employed because of their availability and relative cheapness but these proved unreliable in regions of disturbance in the air flow pattern, such as the eddy zones leeward of dense belts. With the delivery of one counter-type "Sheppard" cup anemometer, now known as the Sensitive Type IV anemometer (Casella & Co., London; Plate 2), in April 1953, vane anemometers were used only in exposed situations as control instruments, other observations of wind velocity being carried out with the cup anemometer. Later, the use of the latter, as control, in conjunction with a hot-wire anemometer (Hastings Instrument Co., Virginia, U.S.A.; Plate 3) for the scattered measurement points was tested but was abandoned in 1954 in favour of standardisation of the instruments used, the Sensitive Type IV anemometer being selected as most suitable for the purpose.

In June 1954 two of these anemometers were obtained on loan from the Meteorological Office and two further instruments were delivered by the manufacturers in August, after the inevitable waiting period. Thus, for the later studies at least, five anemometers of uniform type were available. Whilst falling short of the ideal number required for the investigations, the five instruments resulted in a considerable improvement in the execution of the field work and in the reliability of the data.

Observations of shelterbelt influence on wind velocity were conducted along a measurement line normal to the axis of the belt and extending from 10 shelterbelt-heights windward to 30 heights leeward, the anemometers being exposed at an effective height of 1.5m above ground. Approximately 20 observation points were required usually to cover adequately the distance protection afforded by the shelterbelt. Since the availability of anemometers precluded the simultaneous measurement of wind speeds at all points, observations were distributed over 5 or more measurement periods, generally of 30 min. duration. During the whole operation a control station was operated at a point beyond the influence of the shelterbelt; in practice it was found that the windward limit of the measurement line, i.e. 10h up-wind of the belt, was suitable. The control station was equipped with an anemometer and a small, non-recording, wind direction vane, the latter being observed at the beginning and end of each half-hour period and more frequently when circumstances permitted. The remaining 4 anemometers were dispersed along the measurement line and moved to new positions at the end of each period. The small number of instruments and the narrow range in which they were erected at any one time allowed one man to switch them off and on with the minimum time lag, a second observer operating the control instrument. This procedure and particularly the extension of the measurement period to 30 min. instead of the earlier 20 min. reduced the sources of possible error to a practical minimum.

However, there were certain disadvantages to this method, notably that the wind velocities recorded at all observation points were not simultaneous and, therefore, were liable to be complicated by changes in wind direction. Within limitations, these could be allowed for, by applying corrections according to the effective distance of the observation points from the shelterbelt. Such corrections have been based on the mean wind direction for the particular period, generally the average of two readings. However, wind direction frequently exhibited marked fluctuations, which could not be taken into consideration entirely, even if it had been possible to record the wind direction every two or three minutes. It must be accepted that this fact has limited the accuracy of the data obtained to some small extent, dependent on the prevailing meteorological conditions. As far as possible, measurement periods when the wind direction showed too marked a deviation from the normal to the shelterbelt have been excluded from the data presented. The error could have been avoided only by having sufficient instruments to equip the whole range of measurement at one time and an automatic direction-recording apparatus; the expenditure involved was unfortunately prohibitive.

The wind velocities recorded have been expressed as percentages of the unobstructed wind speed at the same height of measurement.

(ii) Other Microclimatic Factors

In addition to the investigations of wind conditions in the vicinity of shelterbelts, it was considered desirable to conduct simultaneous studies of evaporation rate in the sheltered areas, "thistle" evaporimeters (Plate 5) being erected on the measurement line with the evaporating surface at 1.5m above ground level. These instruments, based on the design of Dr. W. Nägeli of the Swiss Forest Research Institute, were not available in their finalised form until the summer of 1955, owing to difficulties experienced by the respective manufacturers in preparing the requisite porous discs and the flat-ground, recurved flanges of the glass, thistle funnels. Because of the insufficient data obtained to date, the investigations of evaporation rate have not been included in the results presented below.

Detailed studies of factors other than wind velocity and evaporation rate were not attempted owing to their limited application in assessing the efficiency of shelterbelt structures. Similarly, investigations of snow drifting patterns were not practicable, chiefly because of the fact that whilst the majority of isolated shelterbelts are orientated against the prevailing wind, south-westerly in South-East Scotland, snowstorms are rarely accompanied by winds from this direction. In the 1954-55 winter, blizzards occurring some time after the initial falls of snow added further complexity to the drift patterns.

Table 1. WIND-TUNNEL STUDIES: VALUES OF HORIZONTAL VELOCITY RATIOS, V/V_o, DERIVED EXPERIMENTALLY

(All values are shown as percentages)

Height of Measurement 1.0h (5 cm)

Design	Model Width	Distances to Leeward of Model in Multiples of Model Height, h (5 cm)																
		0	1	2	3	4	5	7	10	12	15	20	24	25	27	28	29	30
		Models of Varying Width (Composition as shown in Fig. 20)																
1A	1h	43.18	45.48	44.10	45.00	44.00	45.86	46.14	49.46	50.47	52.29	56.41		68.34				73.28
1B	2h	39.39	38.67	39.58	37.57	39.74	41.13	38.14	41.42	41.30	46.17	51.92		68.23		73.67		
1C	3h	37.50	35.57	33.32	29.88	31.42	31.91	31.76	32.00	35.20	37.00	48.70		63.92		73.96		
1D	4h	35.40	34.43	34.08	35.26	32.38	33.42	34.79	33.97	36.33	42.82	64.36		72.41	74.64			
1E	5h	23.88	22.28	23.39	22.44	22.04	24.56	24.41	26.51	29.86	34.23	50.99		67.50				
1F	7h	33.39	30.69	27.10	26.81	28.54	31.35	34.55	42.60		57.36	71.71	76.43					
1G	10h	39.77	38.21	37.29	38.82	36.26	37.49	38.64	50.46	53.26	64.48	73.10						
1J	15h	36.21	32.54	31.62	35.23	35.35	36.34	46.43	62.10	67.61	73.48							
		Various Cross-sectional Profiles (Composition as shown in Fig. 20)																
2A	15h	36.21	32.54	31.62	35.23	35.35	36.34	46.43	62.10	67.61	73.48							
2B	15h	36.21	35.38	37.01	38.23	46.85	51.82	60.37	70.09	72.41	77.91							
2C	15h	41.27	39.56	44.41	44.87	49.72	54.69	63.92	70.96	74.92	79.11							
3A	5h	42.61	43.42	44.86	39.45	40.29	43.82	45.72	49.45		63.57	74.09		79.45				
3B	5h	49.05	49.97	48.17	48.81	49.71	46.44	44.72	46.20		68.64	76.98		82.88				
3C	5h	52.90	54.48	51.51	53.36	50.66	51.30	51.67	52.64		73.00	79.11		83.75				

TABLE 1 (cont.) Height of Measurement 1.0h (5 cm)

Design	Model Width	Distances to Leeward of Model in Multiples of Model Height, h (5 cm)																
		0	1	2	3	4	5	7	10	12	15	20	24	25	27	28	29	30
3D	5h	42.16	44.87	40.49	40.30	43.25	38.29	41.50	44.20		59.60	75.77		83.07				
3E	5h	23.88	22.28	23.39	22.44	22.04	24.56	24.41	26.51	29.86	34.23	50.99		67.50				
4A	3h	63.75	59.75	62.52	52.58	62.01	58.69	54.70	58.98		59.65	64.25		73.96				
4B	3h	66.34	62.33	63.52	63.84	61.08	52.30	55.64	63.77		70.37	79.73		82.45				
4C	3h	37.50	35.57	33.32	29.88	31.42	31.91	31.76	32.00	35.20	37.00	48.70		63.92		73.96		
5A	1h	80.34	64.71	60.50	63.81	57.25	55.51	63.96	56.08		55.49	66.71		71.20				72.59
5B	1h	43.18	45.48	44.10	45.00	44.00	45.86	46.14	49.46	50.47	52.29	56.41		68.34				73.28
6A	2h	58.26	49.80	49.56	48.95	46.26	45.71	51.59	46.76		53.89	65.55		78.38			78.09	
6B	2h	39.39	38.67	39.58	37.57	39.74	41.13	38.14	41.42	41.30	46.17	51.92		68.23		73.67		
		Model of Gosford Shelterbelt (Construction as shown in Fig. 36)																
7	4h	46.82	46.16	44.15	46.40		42.94	62.62	74.71	79.27	84.65	88.72		90.78				
		Model of Group Structure Shelterbelt (Composition as shown in Fig 38)																
8	5h	62.22	62.94	70.94	67.39	62.10	60.49	64.60	67.08		74.89	77.64		81.51				
		Multiple Barrier, composed of two parallel models, each 1h wide and separated by distance of 13h (Fig. 37)																
		Distances to Leeward of First Barrier in Multiples of Model Height, h (5 cm)																
		0	1	3	5	7	10	12	15	17	19	21	25	28				
9			60.26	56.19	52.93	56.22	58.49	59.99	56.41	56.32	55.34	58.70	65.79	71.31				

TABLE 2. WIND-TUNNEL STUDIES: VALUES OF HORIZONTAL VELOCITY RATIOS, V/V_o, DERIVED EXPERIMENTALLY
(All values shown as percentages)

Height of Measurement 0.6h (3 cm)

Design	Model Width	Distances to Leeward of Model in Multiples of Model Height, h (3 cm)																
		0	1	2	3	4	5	7	10	12	15	20	24	25	27	28	29	30
		Models of Varying Width (Composition as shown in Fig. 20)																
1A	1h		39.46	37.03	32.73	34.84	34.64	28.78	28.54		35.58	47.02		59.21				65.34
1B	2h	$\overline{23}.00$	$\overline{26}.45$	$\overline{28}.03$	$\overline{28}.78$	$\overline{32}.07$	$\overline{32}.07$	$\overline{34}.84$	$\overline{35}.66$	$\overline{38}.35$	$\overline{34}.81$	31.16		53.11		62.53		
1C	3h	$\overline{9}.258$	$\overline{36}.04$	$\overline{40}.53$	$\overline{37}.98$	$\overline{40}.70$	$\overline{40}.53$	$\overline{42}.58$	$\overline{44}.08$	$\overline{43}.97$	$\overline{34}.89$	37.79		60.32		65.82		
1D	4h	$\overline{39}.27$	$\overline{39}.27$	$\overline{38}.35$	$\overline{39}.99$	$\overline{39}.09$	$\overline{41}.06$	$\overline{44}.72$	$\overline{45}.82$	$\overline{43}.08$	$\overline{33}.42$	43.78		61.67	64.42			
1E	5h	$\overline{41}.40$	$\overline{40}.88$	$\overline{41}.06$	$\overline{42}.08$	$\overline{44}.72$	$\overline{43}.09$	$\overline{45}.66$	$\overline{48}.76$	$\overline{44}.63$	$\overline{32}.64$	44.55		62.04				
1F	7h	$\overline{39}.39$	$\overline{40}.53$	$\overline{42}.26$	$\overline{43}.59$	$\overline{44}.72$	$\overline{46}.90$	$\overline{46}.76$	$\overline{45}.42$	$\overline{33}.88$	23.00	52.97	63.72					
1G	10h	$\overline{45}.20$	$\overline{46}.44$	$\overline{45}.35$	$\overline{45}.98$	$\overline{47}.51$	$\overline{46}.97$	$\overline{43}.31$	$\overline{25}.05$	19.17	40.92	60.20						
1J	15h	$\overline{45}.88$	$\overline{47}.74$	$\overline{48}.79$	$\overline{47}.40$	$\overline{41}.59$	$\overline{35}.84$	5.423	39.81	47.62	59.82							
		Various Cross-sectional Profiles (Composition as shown in Fig. 20)																
2A	15h	$\overline{45}.88$	$\overline{47}.74$	$\overline{48}.79$	$\overline{47}.40$	$\overline{41}.59$	$\overline{35}.84$	5.423	39.81	47.62	59.82							
2B	15h	$\overline{41}.46$	$\overline{42}.07$	$\overline{41}.27$	$\overline{37}.30$	$\overline{28}.28$	$\overline{11}.47$	32.54	48.07	54.50	64.19							
2C	15h	$\overline{37}.84$	$\overline{37}.74$	$\overline{33}.47$	$\overline{25}.54$	12.65	25.63	40.58	52.49	57.81	65.24							
3A	5h	$\overline{44}.24$	$\overline{45}.66$	$\overline{44}.24$	$\overline{48}.10$	$\overline{47}.36$	$\overline{48}.40$	$\overline{50}.58$	$\overline{50}.06$		$\overline{13}.77$	46.67		59.44				
3B	5h	$\overline{41}.92$	$\overline{43}.41$	$\overline{45}.04$	$\overline{43}.75$	$\overline{46}.44$	$\overline{47}.06$	$\overline{48}.99$	$\overline{41}.46$		41.68	57.86		67.50				
3C	5h	$\overline{38}.91$	$\overline{39}.09$	$\overline{39}.46$	$\overline{40}.70$	$\overline{40}.70$	$\overline{42}.46$	$\overline{43}.09$	$\overline{34}.89$		40.98	59.26		68.06				

(N.B. Barred Figures represent negative values, e.g. $\overline{23}.00$)

TABLE 2 (cont.) Height of Measurement 0.6h (3 cm)

Design	Model Width	Distances to Leeward of Model in Multiples of Model Height, h (5 cm)																
		0	1	2	3	4	5	7	10	12	15	20	24	25	27	28	29	30
3D	5h	$\overline{38.73}$	$\overline{38.17}$	$\overline{39.99}$	$\overline{40.18}$	$\overline{41.75}$	$\overline{42.42}$	$\overline{44.87}$	$\overline{43.32}$		27.82	53.19		65.69				
3E	5h	$\overline{41.40}$	$\overline{40.88}$	$\overline{41.06}$	$\overline{42.08}$	$\overline{44.72}$	$\overline{43.09}$	$\overline{45.66}$	$\overline{48.76}$	$\overline{44.63}$	$\overline{32.64}$	44.55		62.04				
4A	3h	20.70	$\overline{12.53}$	$\overline{23.91}$	$\overline{27.52}$	$\overline{30.47}$	$\overline{31.39}$	$\overline{33.81}$	$\overline{35.85}$		$\overline{12.04}$	45.56		59.43				
4B	3h	30.70	$\overline{8.45}$	$\overline{20.35}$	$\overline{22.37}$	$\overline{26.99}$	$\overline{27.52}$	$\overline{31.85}$	$\overline{33.21}$		29.24	53.31		64.74				
4C	3h	$\overline{9.258}$	$\overline{36.04}$	$\overline{40.53}$	$\overline{37.98}$	$\overline{40.70}$	$\overline{40.53}$	$\overline{42.58}$	$\overline{44.08}$	$\overline{43.97}$	$\overline{34.89}$	37.79		60.32		65.82		
5A	1h	97.83	72.59	61.41	54.51	49.57	44.40	39.99	36.45		37.55	43.79		53.96				59.82
5B	1h		39.46	37.03	32.73	34.84	34.64	28.78	28.54		35.58	47.02		59.21				65.34
6A	2h	98.77	49.71	32.29	19.27	12.53	7.56	$\overline{14.64}$	$\overline{19.27}$		$\overline{28.93}$	51.88		61.93			69.26	
6B	2h	23.00	$\overline{26.45}$	$\overline{28.03}$	$\overline{28.78}$	$\overline{32.07}$	$\overline{32.07}$	$\overline{34.84}$	$\overline{35.66}$	$\overline{38.35}$	$\overline{34.81}$	31.16		53.11		62.53		
		Model of Gosford Shelterbelt: (Construction as shown in Fig. 36)																
7	4h	$\overline{49.27}$	$\overline{37.22}$	$\overline{41.40}$	$\overline{38.35}$		$\overline{16.90}$	48.25	62.79	68.06	74.01	77.57		81.16				
		Model of Group Structure Shelterbelt: (Composition as shown in Fig. 38)																
8	5h	26.45	25.64	26.18	25.64	26.73	25.35	27.77	30.98		39.88	46.59		58.42				

Multiple Barrier, composed of two parallel models, each 1h wide and separated by distance of 13h (Fig. 37)

Design	Model Width	Distances to Leeward of First Barrier in Multiples of Model Height, h (5 cm)												
		0	1	3	5	7	10	12	15	17	19	21	25	28
9			42.92	35.26	32.51	32.51	22.37	27.77	18.96	21.32	29.09	37.58	48.91	54.43

(N.B. Barred Figures represent negative values, e.g. $\overline{38.73}$)

TABLE 3. WIND-TUNNEL STUDIES: VALUES OF HORIZONTAL VELOCITY RATIOS, V/V_o, DERIVED EXPERIMENTALLY
(All values shown as percentages)

(Height of Measurement 0.2h (1 cm)

Design	Model Width	Distances to Leeward of Model in Multiples of Model Height, h (5 cm)																
		0	1	2	3	4	5	7	10	12	15	20	24	25	27	28	29	30
		Models of Varying Width (Composition as shown in Fig. 20)																
1A	1h		19.18	22.15	16.94	17.86	13.93		12.53	17.18	23.76	39.46		53.64				69.49
1B	2h	$\overline{27.38}$	$\overline{31.54}$	$\overline{31.99}$	$\overline{34.95}$	$\overline{35.52}$	$\overline{38.20}$		$\overline{43.20}$	$\overline{43.18}$	$\overline{39.04}$	24.60		58.01		65.70		
1C	3h	$\overline{36.34}$	$\overline{39.05}$	$\overline{42.48}$	$\overline{45.80}$	$\overline{47.53}$	$\overline{44.40}$	$\overline{47.77}$	$\overline{52.11}$	$\overline{51.48}$	$\overline{41.07}$	44.99		66.62		77.00		
1D	4h	$\overline{40.41}$	$\overline{43.35}$	$\overline{45.58}$	$\overline{47.58}$	$\overline{49.08}$	$\overline{49.87}$	$\overline{51.78}$	$\overline{57.73}$	$\overline{52.16}$	$\overline{24.54}$	47.37		71.57	75.39			
1E	5h	$\overline{42.08}$	$\overline{45.66}$	$\overline{48.77}$	$\overline{49.43}$	$\overline{51.09}$	$\overline{55.21}$	$\overline{55.77}$	$\overline{59.26}$	$\overline{53.62}$	$\overline{29.86}$	47.62		73.91				
1F	7h	$\overline{45.16}$	$\overline{47.51}$	$\overline{50.67}$	$\overline{52.74}$	$\overline{53.87}$	$\overline{56.36}$	$\overline{59.10}$	$\overline{48.79}$	$\overline{41.07}$	19.68	55.21	75.39					
1G	10h	$\overline{53.15}$	$\overline{54.67}$	$\overline{54.78}$	$\overline{55.67}$	$\overline{54.45}$	$\overline{53.26}$	$\overline{46.76}$	$\overline{32.56}$	15.56	46.06	70.71						
1J	15h	$\overline{52.16}$	$\overline{53.79}$	$\overline{53.73}$	$\overline{50.30}$	$\overline{48.09}$	$\overline{38.33}$	$\overline{22.01}$	40.71	55.21	63.81							
		Various Cross-sectional Profiles: (Composition as shown in Fig. 20)																
2A	15h	$\overline{52.16}$	$\overline{53.79}$	$\overline{53.73}$	$\overline{50.30}$	$\overline{48.09}$	$\overline{38.33}$	$\overline{22.01}$	40.71	55.21	63.81							
2B	15h	$\overline{47.73}$	$\overline{50.41}$	$\overline{48.79}$	$\overline{42.80}$	$\overline{31.81}$	$\overline{10.97}$	39.37	59.27	66.96	72.60							
2C	15h	$\overline{40.63}$	$\overline{42.01}$	$\overline{39.94}$	$\overline{32.94}$	$\overline{21.96}$	25.51	41.16	56.52	65.13	71.06							
3A	5h	$\overline{49.43}$	$\overline{52.50}$	$\overline{50.98}$	$\overline{56.06}$	$\overline{53.51}$	$\overline{55.95}$	$\overline{59.62}$	$\overline{59.26}$		$\overline{25.03}$	44.72		65.51				
3B	5h	$\overline{48.08}$	$\overline{49.07}$	$\overline{46.04}$	$\overline{49.01}$	$\overline{53.31}$	$\overline{52.74}$	$\overline{54.76}$	$\overline{45.74}$		45.78	68.08		73.74				
3C	5h	$\overline{42.91}$	$\overline{44.07}$	$\overline{41.71}$	$\overline{45.54}$	$\overline{46.12}$	$\overline{49.34}$	$\overline{49.66}$	$\overline{41.53}$		43.90	64.76		78.70				
3D	5h	43.78	$\overline{42.72}$	$\overline{45.82}$	$\overline{45.08}$	$\overline{47.45}$	$\overline{44.95}$	$\overline{47.61}$	$\overline{46.25}$		27.33	67.35		74.23				

(N.B. Barred Figures represent negative values, e.g. $\overline{27.38}$)

TABLE 3 (cont.) Height of Measurement 0.2h (1 cm)

Design	Model Width	Distances to Leeward of Model in Multiples of Model Height, h (5 cm)																
		0	1	2	3	4	5	7	10	12	15	20	24	25	27	28	29	30
3E	5h	$\overline{42}.08$	$\overline{45}.66$	$\overline{48}.77$	$\overline{49}.43$	$\overline{51}.09$	$\overline{55}.21$	$\overline{55}.77$	$\overline{59}.26$	$\overline{53}.62$	$\overline{29}.86$	47.62		73.91				
4A	3h	$\overline{29}.86$	$\overline{25}.07$	$\overline{31}.85$	$\overline{37}.64$	$\overline{32}.56$	$\overline{37}.37$	$\overline{39}.56$	$\overline{43}.07$		25.51	46.59		64.39				
4B	3h	$\overline{26}.19$	$\overline{36}.20$	$\overline{34}.68$	$\overline{35}.52$	$\overline{34}.06$	$\overline{40}.27$	$\overline{39}.83$	$\overline{43}.33$		17.70	53.42		70.01				
4C	3h	$\overline{36}.34$	$\overline{39}.05$	$\overline{42}.48$	$\overline{45}.80$	$\overline{47}.53$	$\overline{44}.40$	$\overline{47}.77$	$\overline{52}.11$	$\overline{51}.48$	$\overline{41}.07$	44.99		66.62		77.00		
5A	1h	$\overline{5}.590$	9.053	$\overline{17}.57$	$\overline{8}.474$	$\overline{24}.91$	4.407	$\overline{21}.25$	$\overline{27}.33$		4.851			38.25				56.96
5B	1h		19.18	22.15	16.94	17.86	13.93		12.53	17.18	23.76	39.46		53.64				69.49
6A	2h	[illegible]	$\overline{24}.85$	$\overline{25}.42$	$\overline{30}.96$	$\overline{31}.78$	$\overline{34}.64$	$\overline{34}.34$	$\overline{33}.67$		16.18	45.09		71.90			71.57	
6B	2h	27.38	$\overline{31}.54$	$\overline{31}.99$	$\overline{34}.95$	$\overline{35}.52$	$\overline{38}.20$		$\overline{43}.20$	$\overline{43}.18$	$\overline{39}.04$	24.60		58.01		65.70		
		Model of Gosford Shelterbelt: (Construction as shown in Fig. 44)																
7	4h	$\overline{45}.82$	$\overline{47}.88$	$\overline{51}.00$	$\overline{50}.79$		$\overline{47}.67$	23.44	62.15	75.77	81.85	92.79		94.08				
		Model of Group Structure Shelterbelt: (Composition as shown in Fig. 46)																
8	5h	31.26	33.85	34.35	30.73	27.90	25.96	28.67	19.88		28.19	48.12		59.05				

Multiple Barrier, composed of two parallel models, each 1h wide and separated by distance of 13h (Fig. 45)

Design	Model Width	Distances to Leeward of First Barrier in Multiples of Model Height, h (5 cm)												
		0	1	3	5	7	10	12	15	17	19	21	25	28
9			30.57	16.94	13.93	14.33		26.05	24.25	9.817		22.01	44.17	54.11

(N.B. Barred Figures represent negative values, e.g. $\overline{42}.08$)

TABLE 4. WIND-TUNNEL STUDIES: SMOOTHED CURVE VALUES OF HORIZONTAL VELOCITY RATIOS, V/V_0

(Expressed as percentages)

Height of Measurement 1.0h (5 cm)

	Design	Model Width	Distances to Leeward of Model in Multiples of Model Height (5 cm)												
Models of Varying Width:			0	1	2	3	4	5	7	10	12	15	20	25	30
	1A	1h	45	45	44	44	44	45	46	49	50	52	56	68	73
	1B	2h	40	39	39	38	38	38	38	40	41	44	52	68	75
	1C	3h	37	35	33	32	31	31	31	32	35	37	49	64	76
	1D	4h	35	34	34	34	33	33	33	34	36	43	64	72	76
	1E	5h	24	23	23	22	22	23	24	27	30	34	51	68	74
	1F	7h	33	30	27	27	28	30	35	43	49	57	72	76	—
	1G	10h	40	38	37	37	37	38	41	50	53	62	73	—	—
	1J	15h	36	33	32	32	35	37	46	62	68	74	78	—	—
Models of Various Cross-Sectional Profile:	2A	15h	36	33	32	32	35	37	46	62	68	74	78	—	—
	2B	15h	36	35	37	38	47	52	60	70	72	78	81	—	—
	2C	15h	41	40	41	45	50	55	64	71	75	79	82	—	—
	3A	5h	43	43	43	43	43	44	46	49	55	64	74	79	—
	3B	5h	50	49	48	47	46	45	45	46	53	69	77	83	—
	3C	5h	54	53	52	51	51	50	50	53	59	73	79	84	—
	3D	5h	42	41	40	40	40	40	41	44	49	60	76	83	—
	3E	5h	24	23	23	22	22	23	24	27	30	34	51	68	74
	4A	3h	64	62	61	60	59	59	57	56	57	58	64	74	(80)
	4B	3h	66	64	63	62	61	61	61	64	66	70	80	82	(83)
	4C	3h	37	35	33	32	31	31	31	32	35	37	49	64	76
	5A	1h	80	65	61	58	57	56	55	55	56	58	67	71	73
	5B	1h	45	45	44	44	44	45	46	49	50	52	56	68	73
	6A	2h	58	51	49	47	46	46	46	47	49	54	66	78	81
	6B	2h	40	39	39	38	38	38	38	40	41	44	52	68	75
Model of Gosford Shelterbelt	7	4h	47	46	44	43	44	48	63	75	79	85	89	91	—
Model of Group Structure Shelterbelt	8	5h	62	63	71	67	62	61	62	67	71	75	78	82	—
Multiple Barrier	9		62	60	58	56	54	53	56	58	60	56	56	66	75

(N.B. Figures in brackets denote values obtained by extrapolation of curves)

TABLE 5. WIND-TUNNEL STUDIES: SMOOTHED CURVE VALUES OF HORIZONTAL VELOCITY RATIOS, V/V_0

(Expressed as percentages)

Height of Measurement 0.6h (3 cm)

	Design	Model Width	Distances to Leeward of Model in Multiples of Model Height (5 cm)												
			0	1	2	3	4	5	7	10	12	15	20	25	30
Models of Varying Width:	1A	1h	44	39	37	35	33	31	29	29	30	36	47	59	65
	1B	2h	−23	−26	−28	−30	−32	−32	−35	−38	−38	−35	31	53	65
	1C	3h	−33	−36	−38	−39	−40	−41	−43	−44	−44	−35	38	60	67
	1D	4h	−37	−38	−40	−40	−41	−42	−45	−46	−43	−33	44	62	68
	1E	5h	−39	−40	−41	−42	−43	−44	−46	−49	−45	−33	45	62	69
	1F	7h	−39	−41	−42	−44	−45	−47	−47	−45	−34	23	53	65	—
	1G	10h	−45	−46	−46	−47	−48	−47	−43	−25	19	41	60	—	—
	1J	15h	−46	−48	−49	−47	−42	−36	5	40	48	60	69	—	—
Models of Various Cross-Sectional Profile:	2A	15h	−46	−48	−49	−47	−42	−36	5	40	48	60	69	—	—
	2B	15h	−42	−42	−41	−37	−28	−11	33	48	55	64	72	—	—
	2C	15h	−38	−38	−33	−26	13	26	41	52	58	65	73	—	—
	3A	5h	−43	−45	−46	−48	−49	−50	−51	−50	−42	−14	47	59	(64)
	3B	5h	−42	−43	−45	−47	−48	−49	−49	−42	−8	42	58	68	(72)
	3C	5h	−39	−39	−40	−41	−42	−42	−43	−35	−5	41	59	68	(72)
	3D	5h	−39	−39	−40	−41	−42	−43	−45	−43	−10	28	53	67	(70)
	3E	5h	−39	−40	−41	−42	−43	−44	−46	−49	−45	−33	45	62	(69)
	4A	3h	21	−13	−24	−28	−30	−31	−34	−36	−32	−12	46	59	(66)
	4B	3h	31	−8	−20	−24	−27	−29	−32	−33	−22	29	53	65	(69)
	4C	3h	−9	−36	−38	−39	−40	−41	−43	−44	−44	−35	38	60	67
	5A	1h	98	73	61	55	50	44	40	36	36	38	44	54	60
	5B	1h	44	39	37	35	33	31	29	29	30	36	47	59	65
	6A	2h	99	50	32	19	11	3	−9	−19	−26	−29	52	62	69
	6B	2h	−23	−26	−28	−30	−32	−32	−35	−38	−38	−35	31	53	65
Model of Gosford Shelterbelt	7	4h	−43	−42	−41	−38	−32	−17	48	63	68	74	78	81	—
Model of Group Structure Shelterbelt	8	5h	26	26	26	26	26	25	27	31	34	40	47	58	—
Multiple Barrier	9		46	43	38	35	33	33	33	22	28	19	33	49	57

(N.B. Figures in brackets denote values obtained by extrapolation of curves)

TABLE 6. WIND-TUNNEL STUDIES: SMOOTHED CURVE VALUES OF HORIZONTAL VELOCITY RATIOS, V/V_0

(Expressed as percentages)

Height of Measurement 0.2h (1 cm)

	Design	Model Width	Distances to Leeward of Model in Multiples of Model Height (5 cm)												
			0	1	2	3	4	5	7	10	12	15	20	25	30
Models of Varying Width:	1A	1h	25	22	19	17	15	14	12	13	17	24	39	54	69
	1B	2h	–27	–31	–32	–35	–37	–38	–41	–43	–43	–39	25	58	70
	1C	3h	–36	–39	–42	–46	–48	–49	–50	–52	–52	–41	45	67	81
	1D	4h	–40	–43	–46	–48	–49	–51	–54	–56	–52	–25	47	72	82
	1E	5h	–42	–46	–49	–50	–52	–55	–58	–59	–54	–30	48	74	83
	1F	7h	–45	–48	–51	–53	–55	–56	–59	–49	–41	20	55	76	—
	1G	10h	–53	–55	–56	–56	–55	–53	–47	–33	16	46	71	—	—
	1J	15h	–52	–54	–54	–51	–48	–41	–22	41	55	64	74	—	—
Models of Various Cross-Sectional Profile:	2A	15h	–52	–54	–54	–51	–48	–41	–22	41	55	64	74	—	—
	2B	15h	–48	–50	–49	–43	–32	–11	39	59	67	73	79	—	—
	2C	15h	–41	–42	–40	–33	–22	26	41	57	65	71	78	—	—
	3A	5h	–49	–52	–53	–55	–56	–58	–60	–59	–51	–25	45	66	(75)
	3B	5h	–48	–50	–51	–52	–53	–54	–55	–46	–10	46	68	74	(77)
	3C	5h	–42	–44	–45	–46	–47	–48	–49	–42	–8	44	65	79	(82)
	3D	5h	–42	–43	–45	–46	–47	–49	–49	–46	–24	27	67	74	(77)
	3E	5h	–42	–46	–49	–50	–52	–55	–58	–59	–54	–30	48	74	83
	4A	3h	–30	–31	–32	–34	–35	–37	–40	–43	–27	26	47	64	(79)
	4B	3h	–34	–35	–35	–36	–38	–39	–40	–43	–34	18	53	70	(83)
	4C	3h	–36	–39	–42	–46	–48	–49	–50	–52	–52	–41	45	67	81
	5A	1h	3	–1	–5	–8	–12	–16	–21	–27	–22	5	21	38	57
	5B	1h	25	22	19	17	15	14	12	13	17	24	39	54	69
	6A	2h	23	–25	–28	–31	–32	–33	–34	–34	–23	16	45	72	74
	6B	2h	–27	–31	–32	–35	–37	–38	–41	–43	–43	–39	25	58	70
Model of Gosford Shelterbelt	7	4h	–46	–49	–51	–51	–50	–48	23	62	75	83	93	94	—
Model of Group Structure Shelterbelt	8	5h	31	34	34	31	28	26	22	20	22	28	48	59	—
Multiple Barrier	9		34	31	22	17	15	14	14	20	26	24	15	44	56

(N.B. Figures in brackets denote values obtained by extrapolation of curves)

TABLE 7. SUMMARY OF SHELTER EFFECT OF SIX SHELTERBELTS
(Based on Smoothed Curve Values shown in Fig. 51)

Shelterbelt				Wind Velocity Averages as % of Free Wind Velocity													
				Windward			In belt	Leeward (distances in multiples of height, h.)									
Designation	Height ft	Width ft	Density	0-10h	5-10h	0-5h		0-2½h	2½-5h	5-10h	10-15h	15-20h	20-30h	0-5h	0-10h	0-20h	0-30h
Dreghorn	36	64	Medium	89	96	82	69	54	45	54	72	88	98	49	52	66	77
Currieinn No. 1	27	165	Dense	88	99	77	34	17	28	49	72	85	95	23	36	58	70
Shothead No. 1	40	107	Medium	86	94	77	59	41	28	41	65	83	95	35	38	55	69
Shothead No. 2	35	70	Open	90	97	82	65	55	51	65	83	91	97	53	59	73	81
Langwhang	26	78	Open	98	99	96	96	91	77	71	72	80	93	84	78	77	82
East Saltoun	23	50	Medium	92	99	85	57	36	34	48	67	82	95	35	42	59	71
Average Values				90.5	97	83	63	49	43	55	72	85	95.5	46.5	51	65	75
Average Values for Swiss belts of Moderate Penetrability				93	99	87	57	45	35	48	72	85	94	40	44	61	72

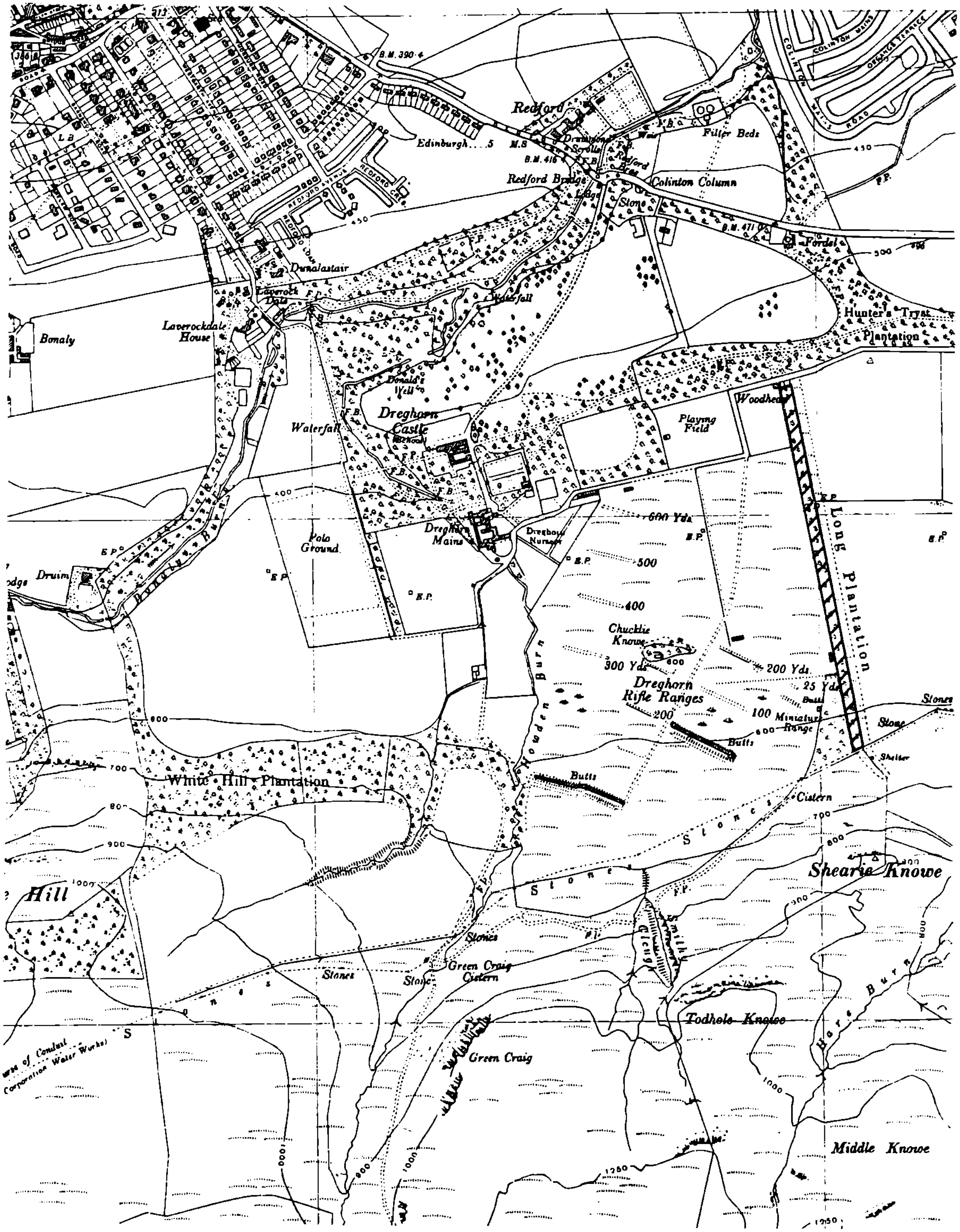


FIGURE 40. Locality map for the Dreghorn shelterbelt. Scale: 6 inches = 1 mile. (Extract from Ordnance Survey Sheet VII NW., Midlothian.)

The consolidation of the drifts before the shelterbelt areas were readily accessible rendered delayed studies of doubtful value.

Occasional instantaneous observations of relative humidity and atmospheric temperature were made in the course of the wind investigations. Relative humidity was calculated from the wet-bulb depression of a whirling hygrometer (Plate 4); for the determination of air temperature dry-bulb thermometers were used. In addition, the cooling power of the wind was measured with the Kata thermometer (Plate 4) during certain of the field studies but this method was used only to demonstrate the suitability or otherwise of the instrument for research of this nature. All observations were made at the standard height of 1.5m above ground except where stated otherwise.

Experimental Results

(a) Dreghorn Shelterbelt

Situated to the south of Edinburgh, on the lowermost northern slopes of Allermuir Hill at the extreme north end of the Pentland Hill range, the Dreghorn Shelterbelt (National Grid map reference NT 230682), frequently referred to as the Long Plantation, occupies a roughly N-S direction, extending for approximately 800 yd between the Dreghorn Castle-Hunter's Tryst road and the 650 ft contour, the latter 250 yd below Shearie Knowe (916 ft). At this point the belt merges with a small plantation on its west side. From the southern end of the belt, proceeding northwards, the slope is moderate to 550 ft, after which it becomes gentle with a slight rise at the northern end adjoining the road; beyond the road the ground falls away to the valley of the Braid Burn. South of the belt the gradient rises abruptly after Shearie Knowe to Allermuir Hill (1,617 ft). The aspect is consequently northerly and, owing to the general topography to the south and south and south-west, the prevailing wind is locally west in direction; this is evident from the deformation of the trees in the shelterbelt.

The belt lies on the boundary of Dreghorn Castle (War Department) property, adjoining Swanston Farm to the east, the latter benefiting from the shelter afforded. Arable ground to the north-east of the belt produced cereal crops during 1953 and 1954. At higher elevations the cultivated land gives way to enclosed pasture on this side of the belt. Rough grazing, presently used for military purposes, occupies the ground to the west of the belt. A certain amount of shelter to the belt itself is afforded against northerly winds by the wooded policies surrounding recently demolished Dreghorn Castle.

About 280 yd from the northern end of the shelterbelt an electricity route, 20 yd wide, passes through the belt more or less at a right angle to the axis; in this section only the marginal hedge and dyke remain.

The belt is 64 ft in width, bounded on the east by a drystone dyke 4½ ft high and on the west by a hawthorn hedge allowed to grow up to an average height of 12 ft, branches overhanging up to 10 ft westwards and absent below 3½ ft, evidently the height of earlier trimming. The hedge is relatively complete, with a few gaps of 3 ft or more between stems, although in the absence of a fence the belt is not stock-proof on this side. The area of the belt is approximately 3.5 acres, excluding the small plantation adjoining on the south-west. A stocking of 548 stems per acre in the lower part comprised in 1954 65.2% Scots pine, 8.0% sycamore, 7.5% oak, 6.0% elm, 5.5% ash, 4.7% rowan, 1.6% birch and 1.5% beech, holly and alder. Average quarter-girth measurements at breast height (B.H.Q.G.) were: Scots pine—6 in., sycamore—7 in., oak, elm, ash—6 in., rowan—4½ in., birch—6½ in.

In height the belt varies from 27 ft on the exposed margin to 42 ft on the east, the average being 36 ft. In spite of height variation, there is one canopy only (Plate 11), understorey and undergrowth being absent throughout. The ground cover is a soft grass association. In transverse section (Plate 12) the principal feature, apart from the windswept appearance of the conifers, is the central core of almost pure Scots pine, flanked on either side by leaf-tree species.

Observations of wind velocity recorded in Fig. 41 were made in October 1954, before the autumn leaf-fall was far advanced and when the geostrophic wind was south-westerly, as determined from cloud movement, although the fairly continuous ground wind never deviated more than 19° from the normal to the belt during the field experiments and averaged 17 ft/sec in velocity. On an earlier occasion, with mild sunny conditions, the W wind suddenly changed to SSE, blowing down the slopes of Caerketton Hill to the east of Allermuir, and operations had to be abandoned.

Relative velocities recorded at the various measurement points on either side of the shelterbelt and on a measurement line normal to the belt were as follows:

Windward:

Distance from belt:	10h	9h	7h	4h	3h	2h	1h	0h
Relative Velocity, %:	100	96.9	95.4	87.6	87.4	86.5	77.7	81.8

Leeward:

Distance from belt:	0	1h	2h	3h	5h	7h	15h	20h	28h
Relative Velocity, %:	37.7	39.0	49.0	43.6	49.6	52.3	80.4	96.5	100

Interior of Belt:

Relative Velocity, %: 68.6

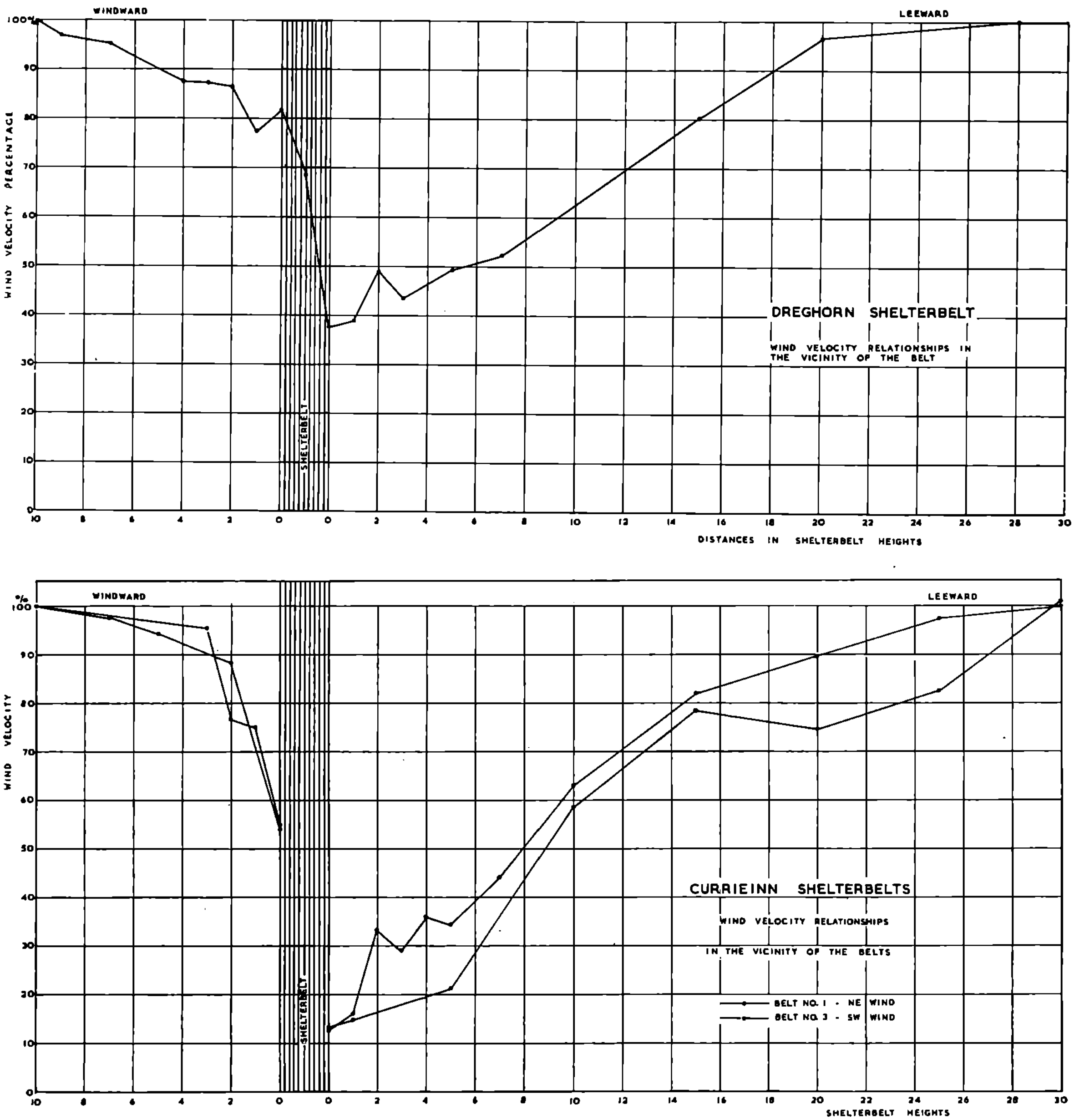


FIGURE 41. Relative wind velocities, in percentages of the free-wind speed, in the vicinity of the Dreghorn and Currieinn shelterbelts. Measured at 1.5m above ground.

These results show a gradual deceleration of the free wind as it approaches the shelterbelt with a slight increase in velocity as it filters through the windward margin. Within the shelterbelt the velocity decreases again until the minimum point of the curve is reached on the leeward side. A casual examination of the relative velocity values suggests that this minimum point occurs at the leeward margin of the belt. This is, in fact, due to the presence of the wall and not to the structure of the belt. However, at 2h, the shelterbelt again becomes the dominant influence and the true minimum of the curve is attained at 3h. From this point a gradual increase in velocity occurs until the unobstructed wind speed is restored at 28h.

Measurements of atmospheric temperature made during the course of the wind studies on a mild, sunny afternoon were as follows:

Windward:
Distance from belt:
10h 9h 8h 7h 6h 5h 3h 2h 1h 0h
Air Temperature, °F:
55 55 55 55 55 55.5 55 55 55.5 56

Leeward:
Distance from belt:
0h 1h 2h 3h 4h 5h 6h 7h 8h 9h 10h 12-28h
Air Temperature, °F:
56.5 57 57 57 57 57 57 57 57 57 56.5 55

Interior of Belt:
Air Temperature, °F: 57

Near the windward margin of the belt a temperature increase occurred, due partly to the wind abatement but also to radiation effect. On the leeward margin a slight fall in temperature may be attributed to shading but, further leeward, the influence of the shelterbelt is apparent. It is interesting to note here that the 2°F increase in temperature corresponded very closely with a wind velocity less than 60% of its unobstructed speed.

Relative values of the cooling power of the wind, determined with a Kata thermometer, were:

Windward:
Distance from belt:
10h 9h 6h 5h 4h 3h 2h 1h 0h
Cooling power, %:
100 100 95 95 90 86 86 95 95

Leeward:
Distance from belt:
Cooling power, %:
0h 1h 2h 3h 4h 5h 6h-15h 20h 28h
Cooling power, %:
73 68 73 76 73 76 76 84 100

Interior of Belt:
Cooling power, %: 83

Although subject to the inaccuracies of the instrument these values indicate a distinct reduction in the wind's cooling power in the sheltered zone afforded by the belt.

Measurements of relative humidity and saturation deficit carried out in conjunction with the above studies were rejected owing to the fact that, after a long period of heavy rainfall, the ground to the west of the belt was waterlogged; consequently, a higher relative humidity was found on the windward side than on the leeward ground, the latter being bare stubble at that time and well-drained.

(b) **Currieinn Shelterbelts**

The Currieinn shelterbelt system of five contiguous belts (National Grid map reference NT 385590), in the parish of Borthwick, Midlothian, stands on exposed ground originating from the northern extremity of the Moorfoot Hill range and falling away gradually to the Gore Water on the west and the Tyne Water on the north and north-east. The elevation of the belts approaches 850 ft above sea level, the ground to the south sloping very slightly to 821 ft on the main A-7 Edinburgh-Galashiels road at its junction with the Halflaw Kiln farm road, after which altitude increases slowly across Middleton Moor and then moderately to the Moorfoot Hills, a series of smoothly rounded hills frequently exceeding 2,000 ft in elevation. The shelterbelts are exposed on all sides but the predominant aspect is slightly north-easterly.

The belts extend over two adjacent farms, Nos. 1-4 (Fig. 42) on Currieinn Farm and No. 5 on Middleton Mains Farm, both formerly part of Borthwick Estate and acquired by Lord Strathcona in 1952. A sixth belt, running south-westerly from the junction of belts 2 and 3, appears to have been cleared 20-30 years ago and has reverted to pasture, only the boundary beech and hawthorn hedgerow remaining.

All belts in the system are 55-60 yd in width and are stocked with a mixture of Scots pine and Norway spruce, planted in alternate rows at a spacing between and within rows of 3½ ft. At 25-30 years of age, the belts are unbrashed and unthinned, dense and impenetrable and the spruce has been suppressed almost entirely. The average height in 1954 was 27 ft with few stems measuring more than 4 in. B.H.Q.G. Surrounding the belts a hedgerow of beech and hawthorn, their crowns forming an almost continuous screen from 5 ft to about 18 ft above ground, has preserved the crowded belts against wind damage. Within this protective margin a shallow ditch and narrow path occupy a distance of 3-4 yd before the coniferous stand commences. It would appear that the hedgerows are remnants of an earlier rotation on this site; this suggestion is supported by the old hedgerow surrounding the cleared belt.

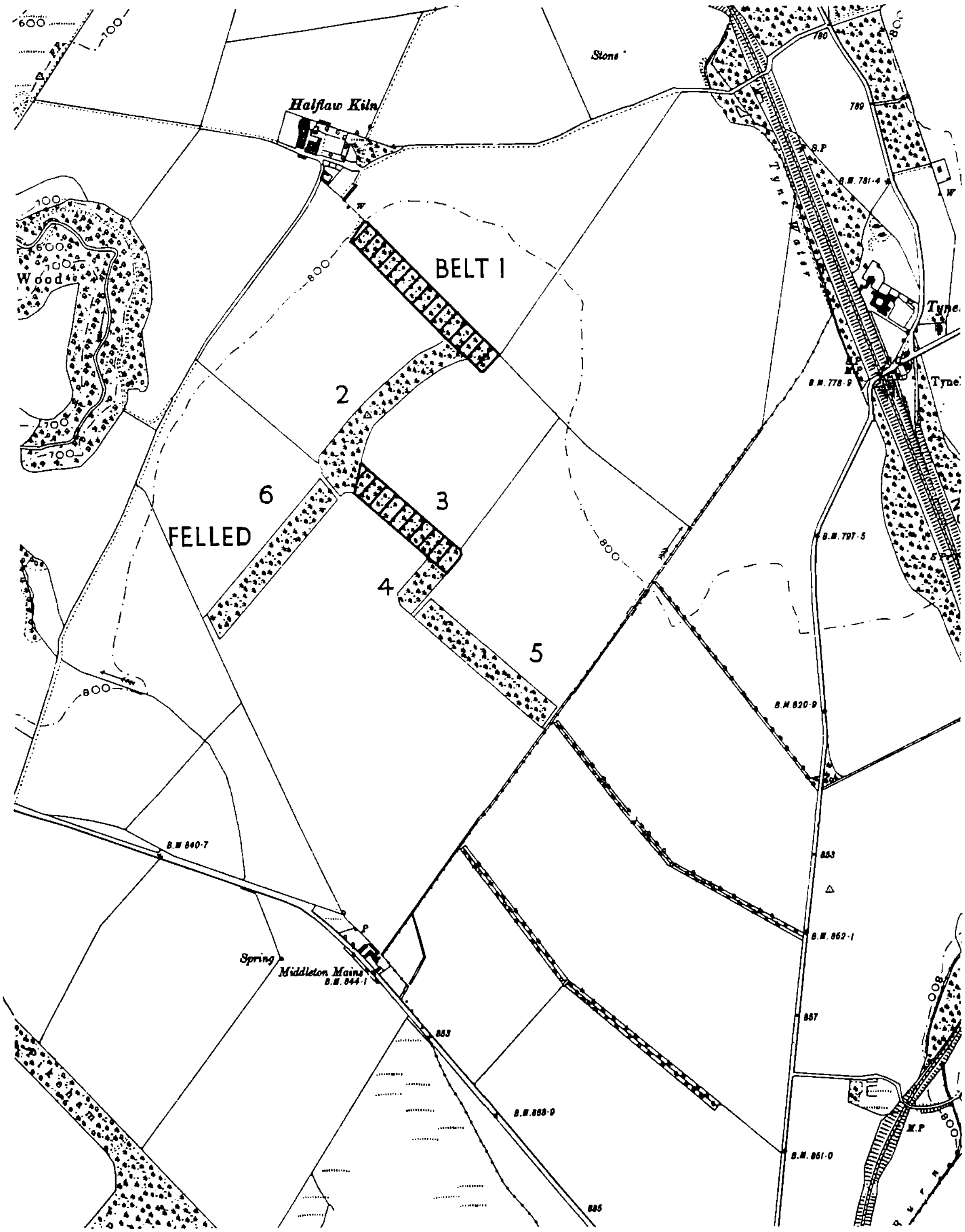


FIGURE 42. Locality map for the Currieinn shelterbelts. Scale: 6 inches = 1 mile. (Extract from Ordnance Survey Sheet XV SW., Midlothian.)

Wind investigations were carried out in 1953 and 1954 in the vicinity of belts 1 and 3 with NE and SW winds respectively (Fig. 41). In the case of the former winter conditions prevailed, the hedgerows being leafless at the time of the studies. The following relative wind speeds were observed:

Windward:

Distance from belt:	10h	3h	2h	1h	0h
Relative Velocity, %:	100	95.7	77.0	75.0	55.0

Leeward:

Distance from belt:	0h	1h	2h	3h	4h	5h
Relative Velocity, %:	12.7	16.2	33.6	29.2	36.1	34.6
Distance from belt:	7h	10h	15h	20h	25h	30h
Relative Velocity, %:	44.2	63.0	82.0	89.7	97.5	100

These results show a gradual decrease of wind speed towards the windward margin and the minimum point of the curve actually at the leeward edge, as might be expected from the density of the belt. At this point the wind speed is reduced to 12.7% of its unobstructed value, which averaged 20 ft/sec throughout with very constant direction normal to the shelterbelt. Further leeward the resumption of velocity follows a smooth curve with a fairly steep gradient. Some irregularity in the readings at 2-4h may have been due to turbulence on the lee side of the belt.

Measurements near belt 3 were carried out in summer conditions when the wind speed averaged 12 ft/sec and the direction SW, again more or less normal to the belt but deviating occasionally towards the west. Recorded velocities were:

Windward:

Distance from belt:	10h	7h	5h	2h	0h
Relative Velocity, %:	100	97.4	94.3	88.5	54.0

Leeward:

Distance from belt:	0h	1h	5h	10h	15h	20h	25h	30h
Relative Velocity, %:	13.5	15.0	21.4	58.7	78.5	74.8	82.8	101.0

No readings were utilised in the turbulent zone between 2h and 4h owing to the anemometer type available at that time. The curve for these results show, however, a similar course to that for belt 1, although a greater shelter effect is apparent throughout and particularly up to 10h leeward of the belt. This may have been due to the additional shelter occasioned by the hedgerows being in leaf or the slightly different character of the two belts. It will be noticed that a second depression in the curve occurs after 15h; this is doubtless due to the distance protection afforded by belt 2, as would be expected if the wind veered to the west. Thus, between 15h and 30h leeward of the belt, the sheltered zones of the two belts would overlap. Any further reduction in velocity found beyond 30h could be attributed entirely to belt 2. In this case, such a question did not arise, probably because the wind backed again.

Turbulence to the lee of belt 3 was observed on a further occasion when the direction of the wind was approximately WSW and maintained a constant direction 60° from the normal to the belt and was moderate and gusty. Whereas the average velocity at 1h throughout was 15% of the free wind speed, the direction at this point changed rapidly through a wide range, frequently being parallel to the belt margin and at other times exhibiting a reverse current towards the belt.

Air temperatures observed in the vicinity of belt 1 in conjunction with the wind studies were as follows:

Windward:

Distance from belt:	10h	7h	5h	3h	2h	1h	0h
Air Temperature, °F:	42	42	42	42	42	43	43

Leeward:

Distance from belt:	0h	1h	2h	3h	4h	5h	7h	10h	20h	25h	30h
Air Temperature:	43.5	44.5	44	43.5	43	43	42.5	42.5	42	42	42

Under completely overcast, cold, weather conditions, the belt thus showed a small effect on air temperatures. Corresponding values for relative humidity were:

Windward:

Distance from belt:	10h	7h	5h	3h	2h	1h	0h
Relative Humidity, %:	92	92	92	92	92	92	92

Leeward:

Distance from belt:	0h	1h	2h	3h	4h	5h	7h	10h	20h	25h	30h
Relative Humidity, %:	96	96	93	92.5	92	92	92	92	92	92	92

Observations of atmospheric temperature and relative humidity, conducted near belt 3 on a separate occasion, when the wind was SE in direction, light and variable and weather conditions warm and sunny, showed no influence which could be attributed to the belt except a temperature of 50.5°F and a relative humidity of 55.5% within the belt compared with corresponding values on the windward margin of 50.5°F and 49.5% and on the leeward margin of 52°F and 46%. At this time the windward margin was shaded and the leeward margin experiencing direct insolation.

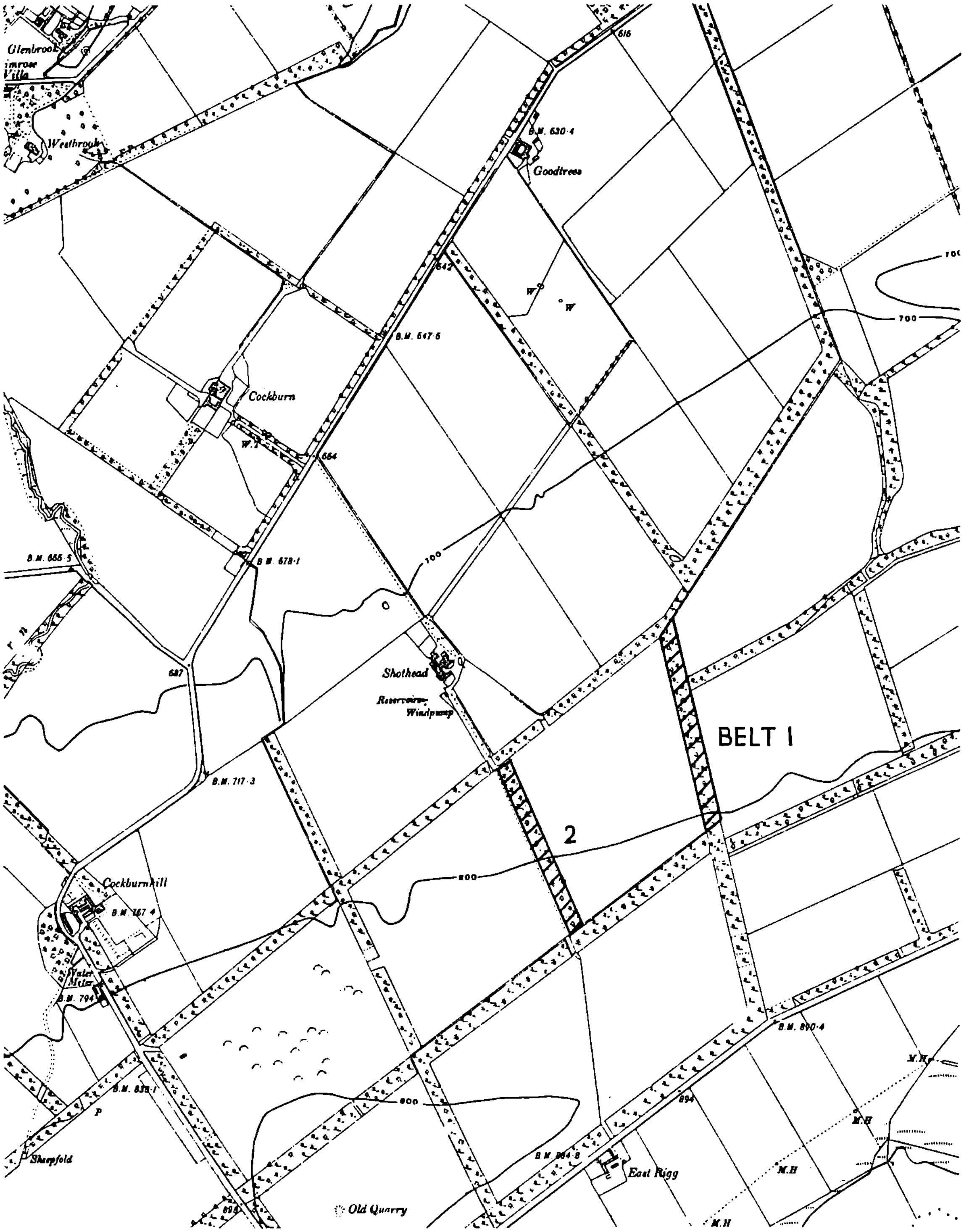


FIGURE 43. Locality map for the Shothead Farm shelterbelts. Scale: 6 inches = 1 mile. (Extract from Ordnance Survey Sheet VI SE., Midlothian.)

(c) **Shothead Shelterbelts**

The Shothead Farm shelterbelts form the inner section of a comprehensive system of belts, formerly extending from the Cock Burn on the west to Balerno on the north-east, and situated on high ground to the north of the Pentland Hill range. A gentle slope towards the Water of Leith gives the area a general northerly aspect, elevation ranging from 900 ft above sea level at the south-west corner of the property to 664 ft at the junction of the farm roadway with the Balerno-Cockburn road on the north-west and 616 ft at the extreme north-east corner of the farm. To the south of the area marginal farmland falls gently to the Bavelaw Burn, thereafter rising in a moderate gradient to Bavelaw Castle, Hare Hill (1,472 ft) and Black Hill (1,636 ft) above Threipmuir Reservoir with higher peaks in the Pentland range further south.

The area is particularly exposed to the south-west winds which are concentrated to some extent by the Pentland Hills. Many of the shelterbelts between the farm march and the Cock Burn are now cleared; the detrimental effect which this clear-felling has incurred on such high-lying arable ground is apparent. On the property west of Shothead remnants only of the old shelterbelts remain.

Formerly owned by the University of Edinburgh, Shothead is now intensively managed as a dairy farm by the present owner, Mr. A. L. Buchanan-Smith.

The shelterbelts are predominantly of coniferous species with an admixture of leaf-trees more concentrated on the margins. Of the two studied, belt No. 1 (National Grid map reference NT 157644) occupies a roughly N-S direction on the eastern boundary of the farm. On the west margin of the belt is a shallow ditch with mound, the latter surmounted by a post and wire fence with scattered hawthorn bushes 6-8 ft high along the fence line and occasional edge-trees of beech. On the eastern border a deeper ditch separates the belt from arable ground, the level of which is about 2½ ft below that of the shelterbelt. A similar fence bounds the belt on this side but hawthorn bushes are sparse and beech rare. The belt is composed of almost pure Scots pine, averaging 610 stems per acre, 40 ft in height and 6 in. B.H.Q.G. at the time of the investigations, with occasional larch, birch and Norway spruce throughout. Ground vegetation is thin, mainly of grass and bracken; no underwood is present. The belt is 107 ft in width.

The second belt, (National Grid map reference NT 153642) more or less parallel to the first but 350 yd further west, is 88 ft in width although a wide ditch and bare strip on the eastern side reduce the effective width to 70 ft. The average height in 1954 was 35 ft with a stocking of approximately 548 stems per acre comprising 90% Scots pine and the remainder scattered larch, beech, Corsican pine, Norway spruce and rowan. Average B.H.Q.G. measurements were 5¼ in. and 4 in. in the case of pine and larch respectively. Towards the north end of this belt wind damage has caused a wide gap which has interfered with the efficiency of the belt.

Measurements of wind velocity in the vicinity of the two belts (Fig. 44) were carried out on separate occasions with SW and NE winds respectively. In the case of belt 1 the free wind velocity was 17-18 ft/sec and approached the belt perpendicularly. Relative velocities recorded along the measurement line were as follows:

Windward:

Distance from belt:	10h	7h	5h	2h	1h	0h
Relative Velocity, %:	93.7	100.9	88.0	78.3	72.6	93.6

Leeward:

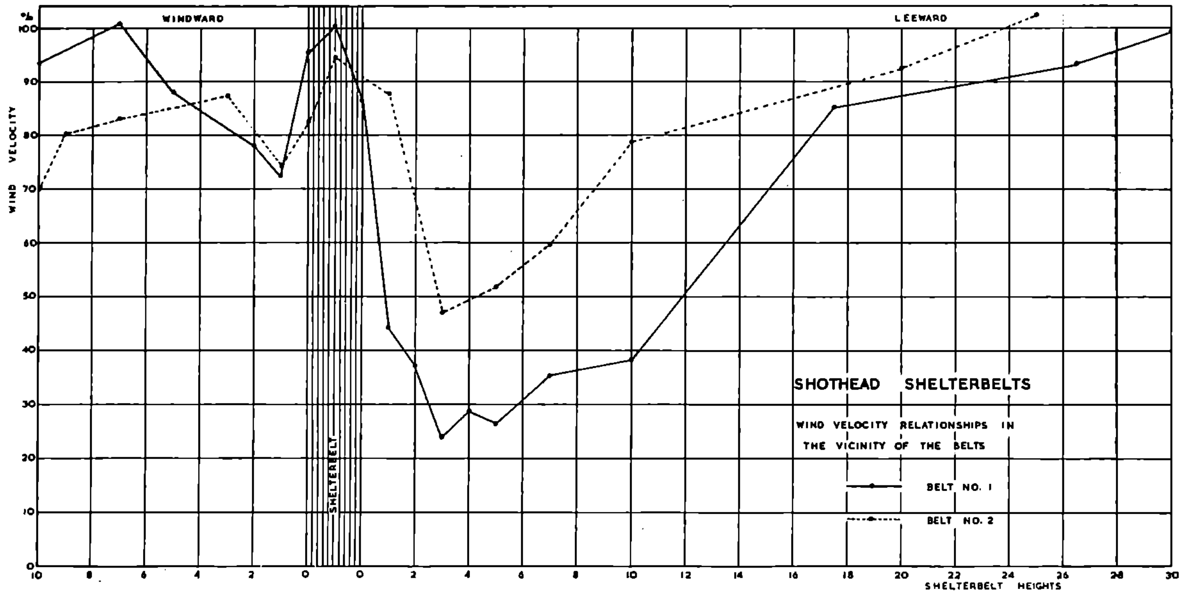
Distance from belt:	0h	1h	2h	3h	4h	5h	7h	10h	17½h	26½h	30h
Relative Velocity, %:	86.5	44.4	37.2	24.0	28.7	26.6	35.3	38.3	85.3	93.3	99.4

Interior of belt:

Relative Velocity, %: 100.6

In these measurements, the cropping arrangement in the field leeward of the belt interfered to some extent with the laying out of a measurement line and observation points had to be selected to avoid undue trespass on growing crops. The 10h point leeward shows an unusually favourable shelter effect, considering the penetrability of the belt; since this point was situated amongst a cereal crop, which was about 18 in. high in this part although averaging 12 in. over the rest of the area, it would seem that, in spite of compensation for the different roughness height, this reading was affected to a considerable degree by the crop. The 17½h point, situated between the cereal strip and a 110-yd wide potato strip, and the 26½h point, between potatoes and a 80-yd wide strip of turnips, would appear to confirm the under-estimation of the 10h station.

At 10h windward of the belt, where 93.7% of the free wind speed was recorded, the influence of belt 2, 230 yd windward of this point, is discernible, the unobstructed wind velocity not yet being resumed. However, at 7h the free wind is restored, a sharp abatement occurring to 1h from the windward margin of the belt. Here a pronounced acceleration takes place, extending to the centre of the belt, after which the curve falls to a minimum at 3h leeward of the belt. The high wind speed within the belt illustrates the open nature of the structure. After 3h the curve rises smoothly to 85.3% at 17½h and little shelter effect is noticeable beyond this distance.



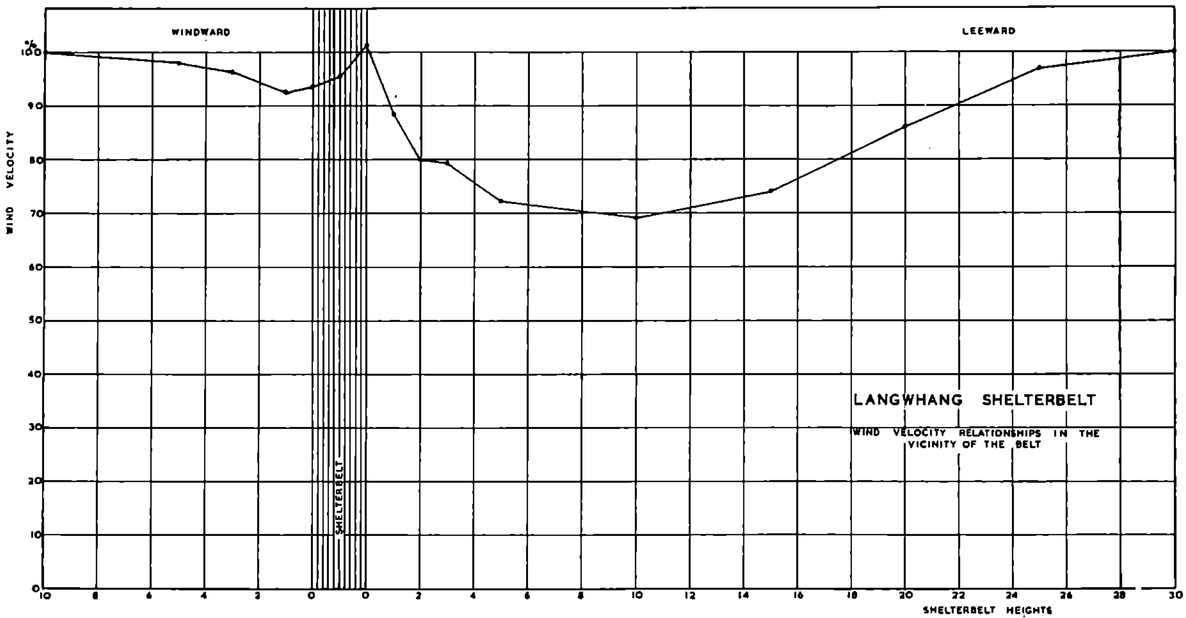


FIGURE 44. Relative wind velocities, in percentages of the free-wind speed, in the vicinity of the Shothead and Langwhang shelterbelts. Measured at 1.5m above ground.

In the wind studies near belt 2 the following relative velocities were observed:

Windward:

Distance from belt:	10h	9h	7h	3h	1h	0h
Relative Velocity, %:	70.0	80.4	83.0	87.3	74.3	82.7

Leeward:

Distance from belt:	1h	3h	5h	7h	10h	20h	25h
Relative Velocity, %:	87.8	47.0	51.9	59.8	78.8	92.4	102.4

Interior of belt:

Relative Velocity, % : 94.6

These results show a marked distance effect of belt 1 with a NE wind, the unobstructed velocity not being restored at any point between the two belts. However, the curve of velocity reduction behind the second belt suggests no cumulative influence of the two belts. Again, an acceleration occurs within the belt, the structure of which is more open as well as narrower than belt 1, and the minimum on the leeward side is found at 3h. The depression of the curve at this point is relatively shallow and rises again sharply, the shelter effect disappearing entirely between 20 and 25h. This may have been due to some extent to the wind-blown gaps in the belt and not exclusively to the structure near the measurement line. However, the results portray the generally poor efficiency of the belt as a whole.

(d) **Langwhang Shelterbelt**

The Langwhang Shelterbelt (National Grid map reference NS 075598), lies to the south-east of the A-70 Edinburgh-Lanark road, commonly called the "Old Lanark" or "Langwhang" road, about 1 mi south-west of Harperrig Reservoir. The elevation of the belt at its south-east end is 950 ft above sea level, falling very slightly to about 930 ft at the north-west end. The general aspect is therefore north-westerly. Further to the north-west beyond the main road the ground slopes very gently to the Crosswood Burn. To the south-east of the belt there is a slight fall to one of the burns feeding Harperrig Reservoir and then a gradual rise to the slopes of the Pentland Hills.

This shelterbelt, typical of many semi-derelict belts in this district, consists of an unfenced stand of Scots pine and Norway spruce, very open and severely deformed and checked by exposure to the prevailing SW wind. The width of the belt is 78 ft, potentially increased to 92 ft by the line of a new fence enclosing a small paddock of improved pasture on the south-west (windward) side of the belt. In 1955 the height of the belt averaged 26 ft and the stocking approximately 228 stems per acre with 90% Scots pine and 10% Norway spruce. Average B.H.Q.G. measurements were 5¾ and 5 in. respectively. No underwood exists, the belt being open to grazing and ground vegetation comprising rough pasture and patches of *Juncus communis* as on the leeward side of the belt. The length of the belt is approximately 300 yd.

Wind velocities measured in the vicinity of the belt when the free wind ranged between 18 and 21 ft/sec showed the following relative values:

Windward:

Distance from belt:	10h	5h	3h	1h	0h
Relative Velocity, %:	100	98.1	96.7	92.8	93.8

Leeward:

Distance from belt:	0h	1h	2h	3h	5h	10h	15h	20h	25h	30h
Relative Velocity, %:	101.6	88.5	80.2	79.6	72.4	69.1	74.0	86.0	97.0	100

Interior of belt:

Relative Velocity, %: 95.6

These figures show that, because of the very open structure of the belt, only a small velocity reduction takes place on the windward side of the belt. Within the belt the wind speed increases, due to jetting between the trees, and reaches a maximum at the leeward edge. From this point the curve falls gently (Fig. 44) to a minimum of 69.1% of the free wind speed at 10h leeward of the belt and then the velocity is restored gradually.

Observations of relative humidity made during the course of the wind studies were:

Windward:

Distance from belt:	10h	5h	1h	0h
Relative Humidity, %:	85	85	85	85

Leeward:

Distance from belt:	0h	1h	2h	3h	5h	10-30h
Relative Humidity, %:	85	87	88.5	87	87	85

Interior of belt:

Relative Humidity, %: 85

Although not corresponding entirely with the wind abatement, these values indicate an effect due to the belt on relative humidity in the leeward sheltered area. No evidence was obtained of a corresponding effect on air temperature.

(e) **East Saltoun Shelterbelt**

The East Saltoun Shelterbelt (National Grid map reference NT 483681) is one of three similar types planted in the neighbourhood by the Saltoun Estate as game "rises" and not primarily for shelter. On agricultural land recently acquired by the Hamilton and Kineill Estates, this shelterbelt lies to the east of East Saltoun village, inclined to the B-6355 road to Gifford which passes the southern end of the belt. From the road and for 260 yd, the width of one field, the belt takes a roughly northern direction, after which the direction changes slightly to NNW for the extent of another field (240 yd), following the field

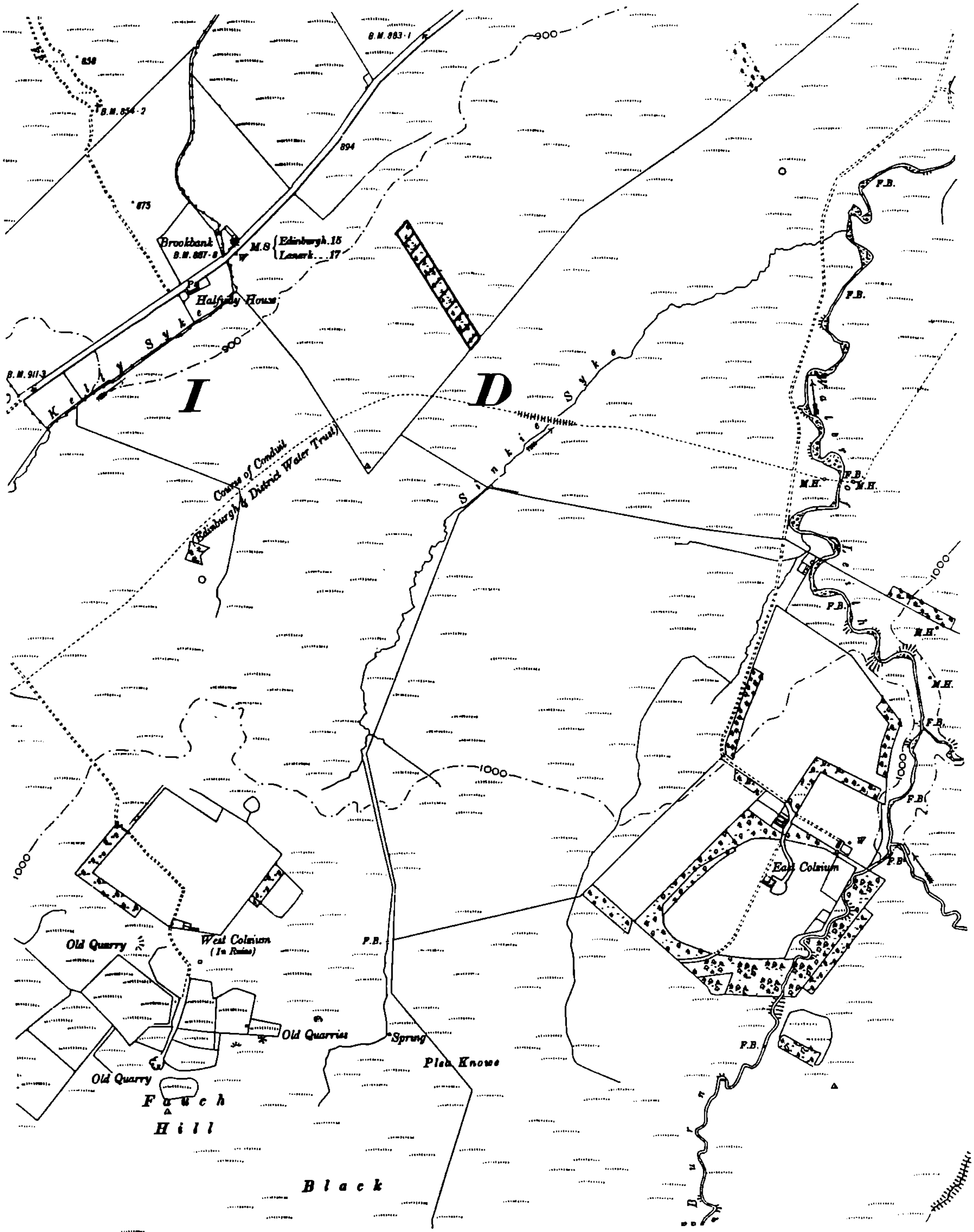


FIGURE 45. Locality map for the Langwhang shelterbelt. Scale: 6 inches = 1 mile. (Extract from Ordnance Survey Sheet XI SE., Midlothian.)

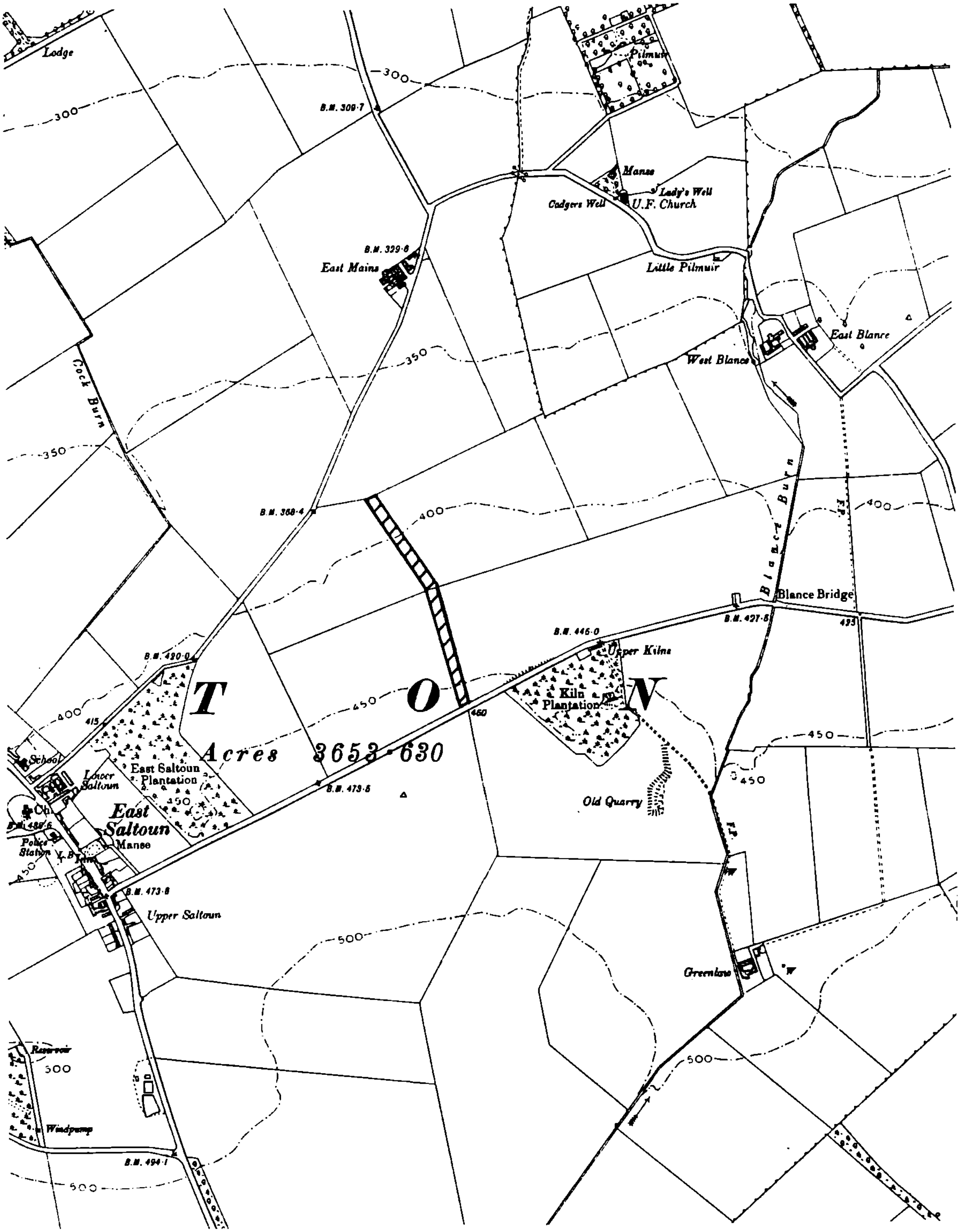
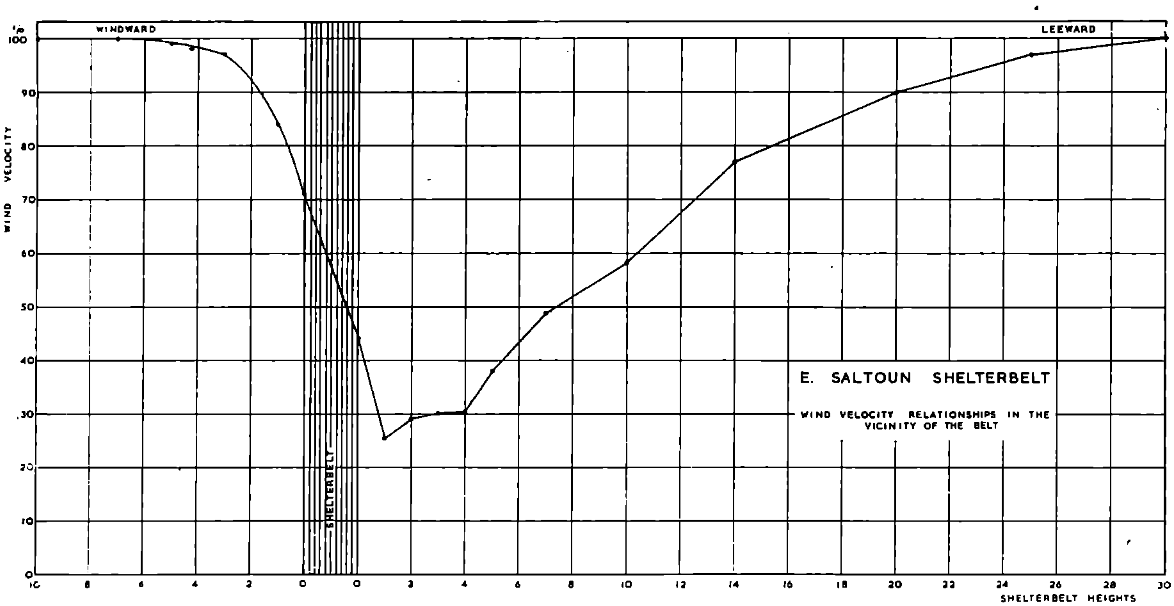


FIGURE 46. Locality map for the East Saltoun shelterbelt. Scale: 6 inches = 1 mile. (Extract from Ordnance Survey Sheet XV NW., East Lothian.)



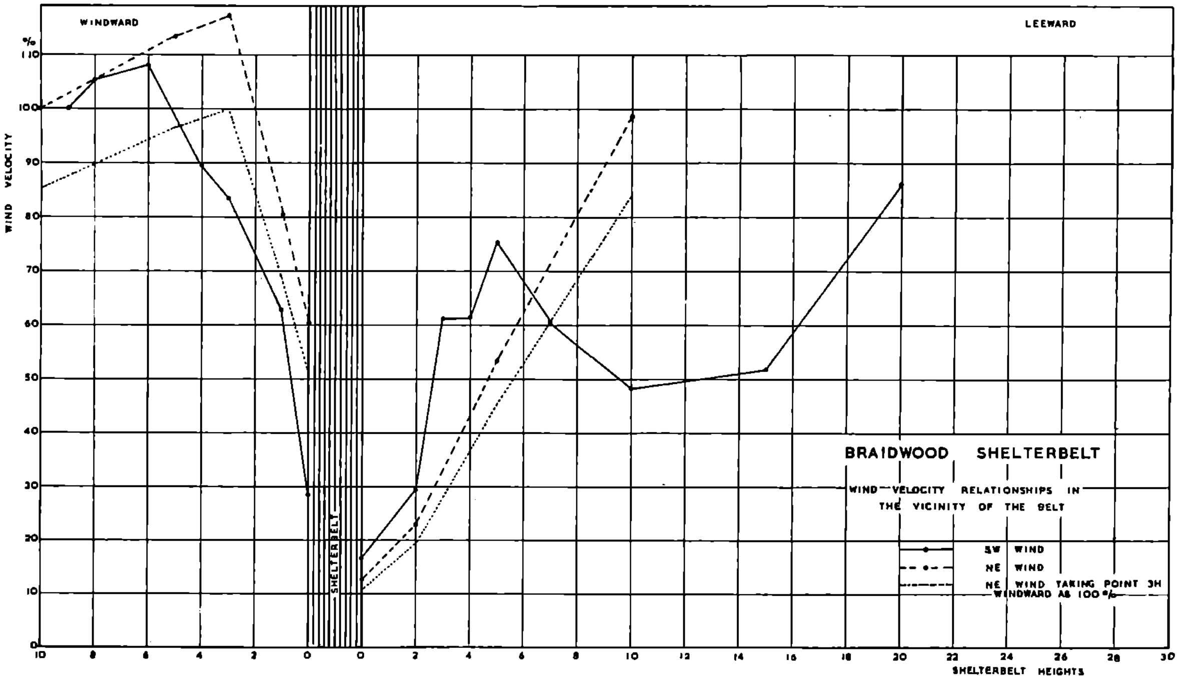


FIGURE 47. Relative wind velocities, in percentages of the free-wind speed, in the vicinity of the East Saltoun and Braidwood shelterbelts. Measured at 1.5m above ground.

boundaries existing at the time of planting. The belt is therefore 500 yd long and the width is 50 ft throughout. The elevation is 450 ft above sea level at the south end of the belt, with relatively level ground over the first field from the road, falling gradually to 400 ft through the second field. To the north the neighbouring land slopes gently to the Tyne Water, 1 mi distant. To the south, beyond the road, the ground rises slightly for 2½-3 mi, thereafter merging into the undulating range of the Lammermuir Hills. To the east and west of the belt the land is fairly level for some distance. The aspect is predominantly northerly.

The southern section of the belt is bounded on the east by an old hawthorn hedge still relatively complete, with two or more heavy branches radiating from each stool, the latter approximately 3 ft apart. Since establishment of the belt the hedge has attained an average height of 12-15 ft but upper branches rarely overhang the arable land. Prior to the planting the hedge appears to have been topped regularly at 5 ft and there are now few branches below this level. The western boundary is a post and wire fence. On the northern section margins are reversed, the fence being on the east and the hedge on the west. The belt is stocked throughout with ash groups at 20-25 yd centres in a matrix of European larch and Scots pine planted at 4½ ft spacing. Within the groups the original planting distance appears to have been 3½ ft; with groups 25-30 ft in diameter there are roughly 40 ash stems per group. The ash has been pruned naturally but no treatment appears to have been carried out. Without the marginal hedge the belt would appear moderately penetrable to the wind. There is a light grass vegetation within the belt. Average B.H.Q.G. measurements in 1955 were: ash—2¼ in., larch—3¾ in., pine—3¼ in. The age is probably 20-25 years. In view of the development stage of the stand complete enumeration of species was impracticable during the time of wind investigations. The height of the belt averages 23 ft.

Measurements of wind velocity near the belt when the direction averaged ENE and occasionally deviated up to 55° from the normal to the belt showed the following relative values:

Windward:

Distance from belt:	10h	7h	5h	3h	1h	0h
Relative Velocity, %:	100	100.4	99.3	97.1	84.1	71.2

Leeward:

Distance from belt:	0h	1h	2h	3h	4h	5h
Relative Velocity, %:	44.3	25.6	29.3	30.1	30.4	38.0
Distance from belt:	7h	10h	16h	20h	25h	30h
Relative Velocity, %:	49.0	58.4	77.0	90.0	97.0	100

In this case, no increased velocity occurs at the windward margin of the belt and the curve (Fig. 47) shows a gradual abatement of wind speed from 7h to windward to the minimum point at 1h to leeward. From here the gradient of velocity resumption is gradual and the shelter effect appreciable as far as 20h.

Observations of relative humidity made on a dry, sunny, spring afternoon showed some variation but averaged 60.5% between 0h and 10h windward, 63.5% between 0h and 5h leeward, 61.5% between 7h and 10h and 61.0% between 10h and 20h. However, at the time of measurement, the newly sown and rolled field to windward of the belt was reflecting a considerable amount of heat and somewhat higher temperatures were recorded in this part than on the leeward side where the ground vegetation was a closely grazed grass sward. Thus the values of relative humidity may be an unreliable indication of the shelterbelt influence on this factor. It may be noted here that, at 25 yd from the belt, 1 ft above the bare soil, relative humidity was 7.7% lower than at 5 ft (approximately 1.5m); corresponding differences above grass 25 yd on the leeward side and within the belt itself were 1.9% higher and 1.6% higher respectively. These figures denote a reverse order in the humidity gradient above the ground between the two types of soil cover, presumably due to the different thermal properties of the bare soil and the grass sward.

(f) **Braidwood Shelterbelt**

Situated on a glacial drift mound, tapering to the north-east, at the foot of the south-east slopes of the Pentland Hills on the farm of Braidwood in Penicuik parish (National Grid map reference NT 194596), the elevation of the Braidwood Shelterbelt varies from approximately 975 ft to 1,050 ft above sea level. The direction of the belt is roughly NW-SE, following the general slope and extending for approximately 150 yd. Above the belt the ground first falls from the mound then rises moderately and afterwards abruptly to Scald Law (1,898 ft).

The form of the mound gives the belt a slightly north-easterly aspect. Immediately east of the belt the ground falls away in a shallow trough, which emerges on the A-702 Edinburgh-Biggar road on the south. West of the belt a slight rise occurs for less than 100 yd, thereafter falling away very abruptly to Eight Mile Burn and presenting a fairly steep face to the prevailing SW wind. This area to the west of the belt, known as Camp Hill and the site of an ancient fort, occupies a commanding position with respect to the main highway and to the land further south which slopes gently to the valleys of the River

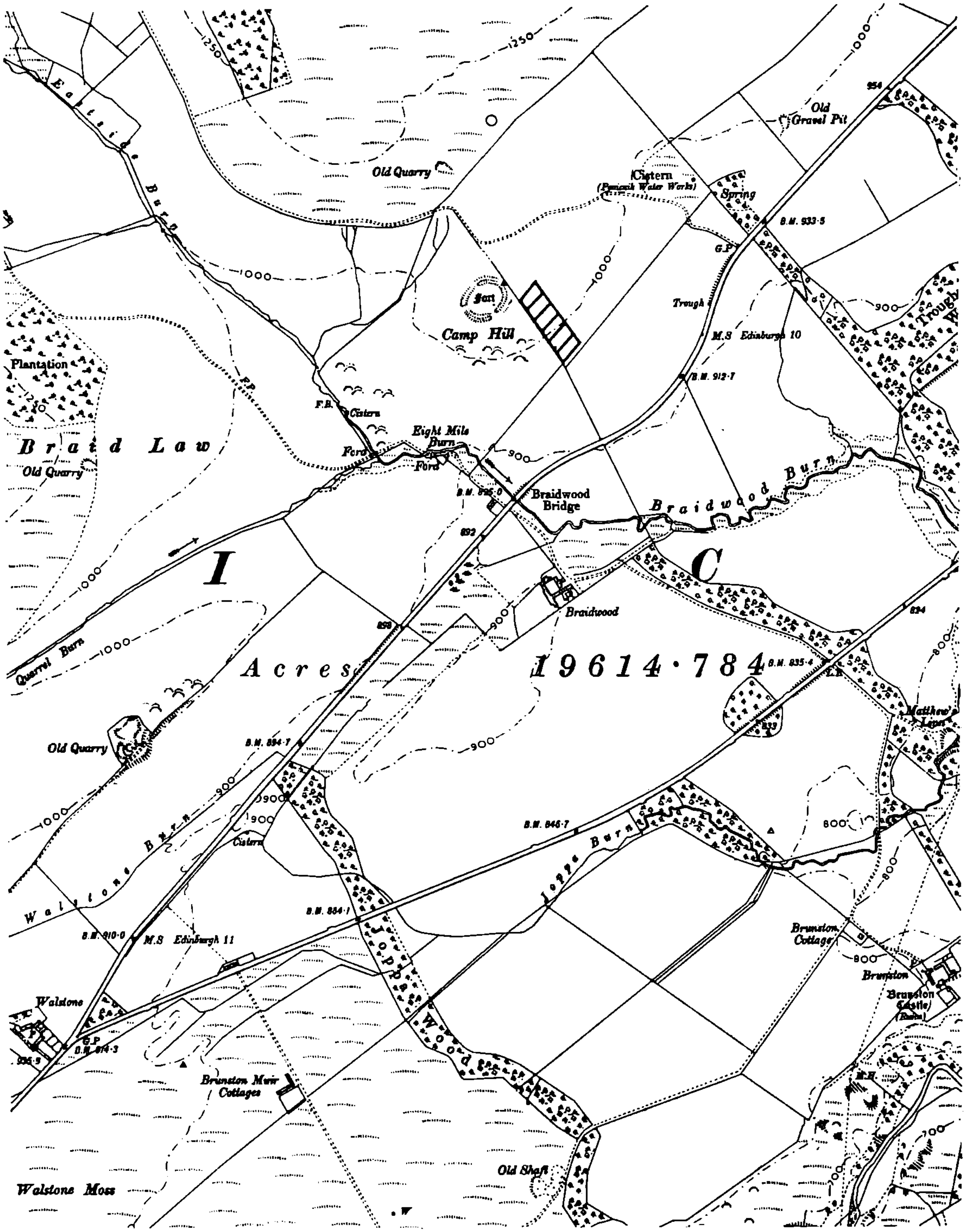


FIGURE 48. Locality map for the Braidwood shelterbelt. Scale: 6 inches = 1 mile. (Extract from Ordnance Survey Sheet XIII SW., Midlothian.)

Esk and the Lead Burn, rising again 5-9 mi distant to the Moorfoot Hills.

The belt is 55 yd (2½ chains) in width, 36 ft in height on the north-east side and 28 ft on the south-west margin (Plate 23). The mixture of larch and pine, the former predominating, has suffered to some extent from lack of timeous thinning but particularly to undermining of the root systems by rabbits. The original planting pattern is not clear but the margins appear to have consisted of alternate rows of larch and pine parallel to the axis of the belt at a spacing within and between rows of 3½ ft. On the north-east side the Scots pine has been almost entirely suppressed and removed although this species becomes dominant on the south-west margin where occasional Sitka spruce occur. There is a scattering of spruce and pine in the centre of the belt, the former frequently wind-thrown. With several small gaps the stocking is approximately 1,100 stems per acre, B.H.Q.G. measurements in 1955 averaging 4¼ in. for pine, 4½ in. for larch and 5¾ in. for spruce. On account of its width the belt is comparatively impenetrable to the wind.

Measurements of wind conditions in the vicinity of the belt were carried out with SW and NE winds averaging 10 and 14 ft/sec in velocity respectively. In the case of the former, the free wind velocity was measured at 9h windward on account of the sudden fall of the ground beyond this point and the leeward measurement line was not extended beyond 20h leeward on account of the topography and the apparent predominance of the latter over the influence of the belt on wind speeds beyond this point. Relative velocities recorded along the measurement line were:

Windward:

Distance from belt:	9h	8h	6h	4h	3h	1h	0h
Relative Velocity, %:	100	105.4	108.1	89.6	83.6	63.0	28.4

Leeward:

Distance from belt:	0h	2h	3h	4h	5h	7h	10h	15h	20h
Relative Velocity, %:	16.9	29.5	61.1	61.6	75.1	60.6	48.3	51.9	86.0

These values show an increase in velocity after the windward control point, due to turbulence in the flow caused by the sharp fall of the ground further windward. A steady decrease in wind speed takes place after 6h from the belt but, owing to the slight incline down to the belt margin, this abatement of the wind may not be attributable entirely to the presence of the belt. After the minimum point of the curve (Fig. 47) at the leeward margin there is a rapid resumption of the unobstructed wind velocity until 5h leeward of the belt, after which a second depression of the curve occurs and extends as far as 20h leeward. This phenomenon may be ascribed to the trough in the topography previously described and it is impossible to determine to what extent the shelter effect is attributable to the presence of the shelterbelt. However, the steep gradient of the curve immediately behind the shelterbelt suggests that, in such a situation, the belt is not efficient because the wind is inclined to roll over the top of the belt due to the fall of the ground parallel with the direction of flow.

The measurements recorded when the wind was NE in direction were:

Windward:

Distance from belt:	10h	5h	3h	1h	0h
Relative Velocity, %:	100	113.5	117.4	80.3	60.5
	(85.2)	(96.7)	(100)	(68.4)	(51.6)

Leeward:

Distance from belt:	0h	2h	5h	10h
Relative Velocity, %:	12.9	23.0	53.5	98.9
	(11.0)	(19.6)	(45.6)	(84.0)

The values shown in brackets are comparative percentages considering the value of the wind speed observed at 3h windward of the belt as 100%, since this must be the true value of the wind which the belt encounters. This increase of velocity towards the belt from 10h to 3h windward illustrates the effect of the slope up to the belt from the hollow mentioned. However, in spite of the gradient, the curve (Fig. 47) shows that the free wind speed is attained very rapidly on the leeward side and at 10h the shelter effect of the belt has virtually disappeared although at this point the ground has already started to fall suddenly. This fact suggests that the general topography east of the belt causes a higher wind velocity from a higher air layer to strike the rising ground immediately to leeward (west) of the belt, in which case the situation renders the belt relatively ineffectual against NE winds.

Observations of relative humidity made in the course of the latter wind studies show a similar trend:

Windward:

Distance from belt:	10h	5h	3h	2h	1h	0h
Relative Humidity, %:	76.0	76.0	71.5	69.0	72.0	72.5

Leeward:

Distance from belt:	0h	1h	2h	3h	5h	10h
Relative Humidity, %:	80.5	77.0	73.0	74.5	69.5	69.0

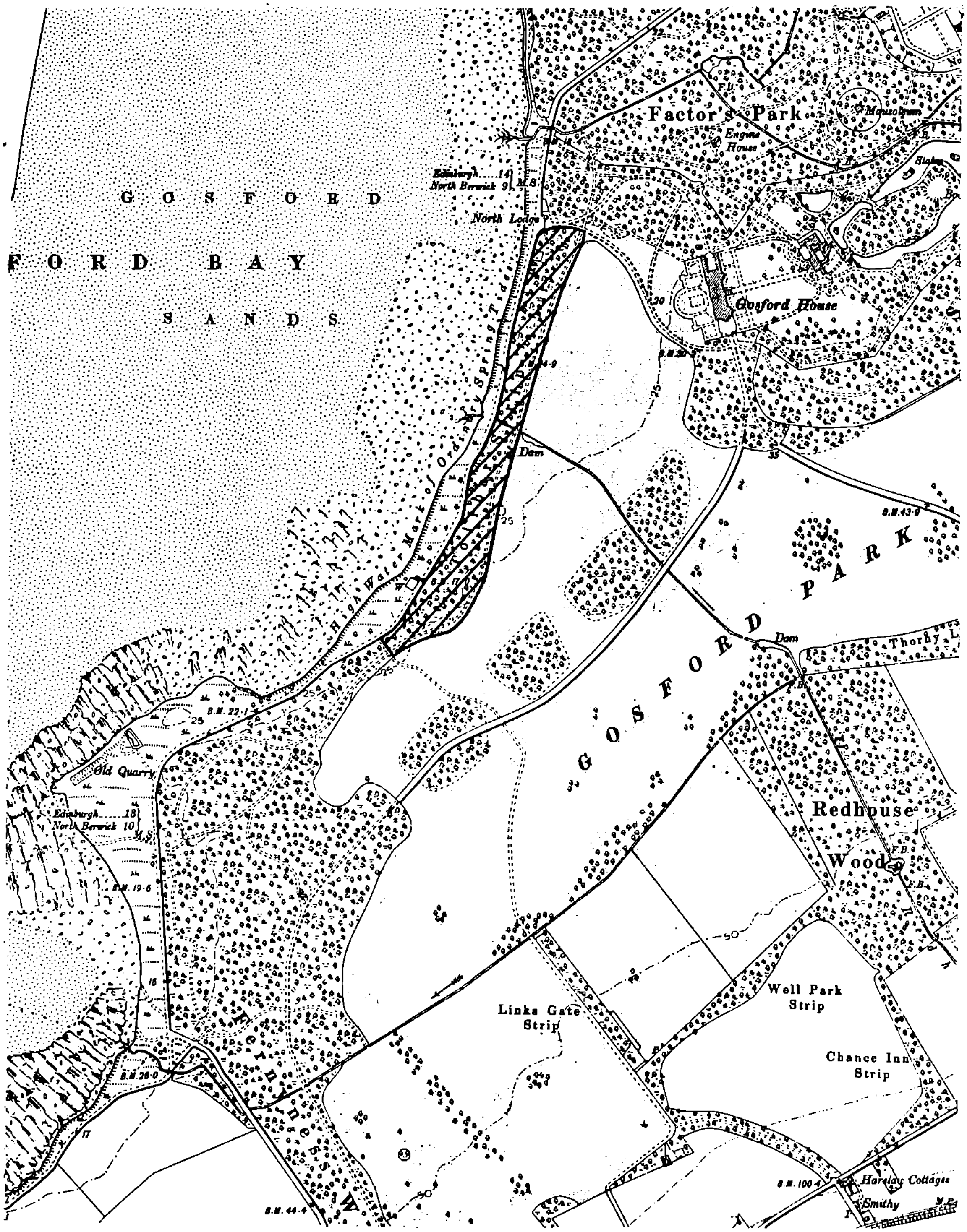


FIGURE 49. Locality map for the Gosford shelterbelt. Scale: 6 inches = 1 mile. (Extract from O.S. Sheet IV S.E., Haddingtonshire.)

(g) Gosford Shelterbelt

The Gosford Estate, owned by the Earl of Wemyss, lies on the southern shore of the Firth of Forth where the coast line, east of Port Seton, takes a sharp sweep to the north to form Gosford Bay. The wooded boundaries of the property, adjoining the bay to the west and north-west of the estate, are consequently severely exposed to the prevailing winds from the Firth. The coastal shelterbelt is formed by a narrow strip of woodland connecting larger policies to the north and south of the bay and provides shelter to Gosford House and surroundings.

In 1796, the young Duke of Rutland, who visited the area, recorded in his privately printed journal: "We now proceeded (from Dirleton) to visit a house building by Lord Wemyss, four miles distant; the road to which lay across an extensive rabbit warren (Gullane). The shell only of the house was completed. . . . Its situation is objectionable in the highest degree; a barren rabbit warren, on a sandy shore stretching on all sides, and the country around being totally destitute of wood or fertilization. We criticized severely the judgement of Lord Wemyss".

Surveys of the estate made about 1807 indicate that practically all the present woodlands around Gosford House had by then been planted, but only a small part of the coastal shelter strip. An important item in the planting was the wall along the coast; built of stone, this was erected in 1800 to give the essential shelter from the salt-laden winds to the first rows of trees, which in turn have sheltered those behind. The benefits which this practice has conferred on the agricultural land leeward of the belt and on the woodlands is readily apparent.

The shelterbelt is thus bounded for the whole of its windward margin, in the form of an arc, by a stone wall, which is separated from the sandy shore by the main A-198 Edinburgh-North Berwick road which skirts Gosford Bay and also, in the south, by a flat grass-covered area raised 4-5 ft above the beach and level with the road. The wall varies somewhat in height according to the slight gradient of the road towards the centre of the bay from its southern end. The trees immediately behind the wall have been wind-pruned to the height of the wall and there is a uniform increase in height inwards to a maximum height of about 40 ft at 150 ft distance from the wall. The width of the belt varies slightly, the leeward margin being irregular, but the average effective width is 150 ft.

The composition of the belt varies. Towards the north of the strip leaf-tree species predominate, with approximately 725 trees per acre in the upper canopy, comprising 38% sycamore, 22% elder, 18% elm, 8% Scots pine, 6% ash and 8% lime, willow and beech. In addition there is a scattered underwood of small elder and elm, amounting to about 1,000 stems per acre, usually in clumps from a common stool, with occasional snowberry and sea buckthorn. Further south, the proportion of Scots and Austrian pines increases to about 40%, in association with leaf-trees. Except on the leeward margin all trees are stunted and dwarfed, with small crowns and poor stem development. But for the outer wall and the continuous, sloping, crown surface, the belt would be classified as very open. Except where small gaps are found in the canopy, no ground vegetation is present.

Wind measurements were conducted to leeward of the belt when the prevailing wind was approximately WSW, with occasional deviations of up to 60° from the normal to the belt. A control station was erected 50 yd windward of the stone wall on rough grass above the beach. No other measurements were possible on the windward side on account of disturbance produced by the continual stream of traffic along the main road. Along the measurement line selected, the wall height was 7 ft above the road although only $5\frac{1}{2}$ ft above the ground level under the trees; the maximum height at the leeward edge in this section was 35 ft. The measurement line selected previously and on which the wind-tunnel studies described earlier were based provided a wall height 9 ft above the road level and 11 ft above the shelterbelt floor; the maximum height of the trees on the leeward margin at this point was 40 ft. These figures show the effect of an increase in the wall height on development of the belt. The latter measurement line was not available during the early spring of 1955 owing to cultivation of the sheltered ground. However, the degree of slope in the canopy is similar in both cases.

The following relative velocities were observed along a line normal to the general direction of the belt, distances being expressed in multiples of 35 ft:

Windward:

Distance from belt:	4-5h
Relative Velocity, %:	100

Leeward:

Distance from belt:

2h	4h	6h	8h	10h	12h	16h	22h

Relative Velocity, %:

34.2	58.5	76.2	85.4	88.3	91.8	94.0	98.0

Interior of belt:

Relative Velocity, %: 31.3

At the time of measurement none of the leaf-trees had flushed, thus accounting for the comparatively high velocity within the belt. From this observation point, which was situated 10 yd from the inside of the wall, the wind speed shows a rapid increase, particularly between 2h and 8h to leeward of the strip (Fig. 50). After 8h the curve flattens out considerably and the gradient of velocity resumption becomes shallow. However, beyond 12h the shelter effect is small, disappearing almost entirely at 22h.

These results of field observations show a similar trend to the curves (Fig. 36) in respect of wind-tunnel studies of a model of this shelterbelt, allowing for the extended distance protection recorded in wind-tunnel experiments in comparison with field studies, this being due to the different stage of boundary layer development (Blenk 1953). There is also a similarity between the Gosford results and the measurements recorded by Nägeli (1953b) on the leeward side of a plantation 21.5 heights wide; in the latter investigations 50% of the free wind speed was observed at 1h, 56% at 2h, 61% at 3h, 68% at 5h, 77% at 8h, 82% at 12h, 89% at 17h, 90% at 23h and 96% at 30h. The Gosford studies show a less favourable shelter effect than behind the wide plantation, at least after 2h from the belt. It is apparent from these investigations that the close, sloping canopy of the Gosford coastal belt does not produce an extended zone of shelter in its lee, but rather the reverse, the gradient of resumed velocity being very steep.

The studies of wind velocity conducted in the vicinity of these shelterbelts reveal characteristic effects on the wind regime produced by the different belt structures. The practical value of this evidence is discussed in the following chapter.

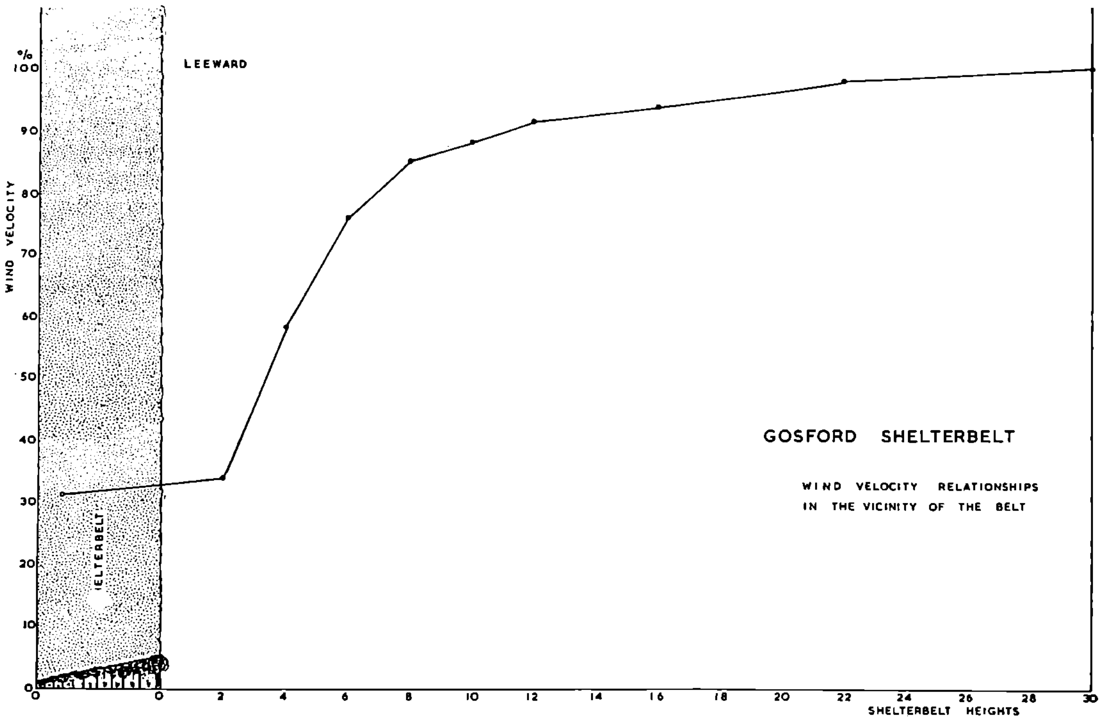


FIGURE 50. Relative wind velocities, in percentages of the free-wind speed, in the vicinity of the Gosford shelterbelt. Measured at 1.5m above ground.

Chapter 11

INTERPRETATION OF RESULTS IN RELATION TO THEIR PRACTICAL APPLICATION

THE EFFECTIVENESS of a shelterbelt is governed by its situation, dimensions, cross-wind shape and structural composition. Adequate consideration of these features is necessary when formulating a scheme of shelter planting. The design of a proposed belt provides for a definite situation and a specified length and width. As far as possible the design should allow also for an approximate final height of the shelterbelt and cross-sectional profile. Structural composition will require to be based on the width, height and cross-sectional shape needed and appropriate provision made in the selection of species, planting pattern and establishment for the gradual development of the optimum structure. Thereafter the belt structure will require to be regulated from time to time in order to maintain its sheltering efficiency and, equally important, its continuity as a stand. Thus, shelterbelt technique may be divided into three stages: the initial design, development of the appropriate structure and its maintenance.

The experimental work described in the foregoing chapters, in conjunction with the published evidence of earlier research, may be discussed under the headings of design, structure and maintenance of belts.

Design of Shelterbelts

In planning a shelter plantation the first consideration, after selection of the site, must be the dimensions. The ultimate height of the belt must be borne in mind at the outset since the area to be sheltered, the distance between parallel belts of a system and the optimum length of the belt are dependent on this dimension.

It would appear that where parallel shelterbelts are planted sufficiently near together it is possible to ensure that at no point between the two belts is the free-wind velocity obtained, although no cumulative effect may be visible behind the second belt. The field studies of wind conditions in the vicinity of two parallel shelterbelts (p. 103) separated by a distance of 350 yd and 35 ft and 40 ft in height respectively revealed that, when the wind approached from the direction of the 35 ft belt, the open-ground wind velocity was resumed at 22h from this belt, i.e. 7h windward of the second belt. However, when the wind direction was reversed, the 35 ft belt became 26h leeward of the 40 ft belt and the free-wind speed was not regained between the two belts. From these results it would seem that, if two parallel belts are separated by a distance equal to 26 times the height of the more windward belt, the entire intervening area will be sheltered to some extent and the unobstructed wind velocity will not occur between the belts.

The wind-tunnel investigations (p. 81) suggest that a cumulative shelter effect may be found in nature behind a system of two parallel screens but the close spacing of the two barriers necessary and the small degree of cumulative shelter obtained are likely to render such an arrangement impracticable. In the laboratory studies a cumulative shelter effect was discerned up to about 16h down-wind of the second screen, which was separated from the first screen by a distance of 13h. However, it would be inaccurate to transfer these quantitative values to field research.

Earlier research has established that the minimum length of a shelterbelt should be approximately 12 times the belt height (and 24 times the height to utilise the full possibilities of distance protection against winds varying in direction up to 45° on either side of the normal to the belt).

In arable districts it is customary for shelterbelts to follow existing field boundaries and the width of such belts is dictated generally by the agricultural value of the land. In the interests of agricultural productivity the limiting width should be that on which it is possible to establish and maintain a shelterbelt of suitable penetrability and structure. This must vary according to site factors and particularly the degree of exposure encountered. On better-class arable land, such as at East Saltoun, at an elevation of 450 ft above sea level, a width of 50 ft would appear to be adequate provided that suitable margins are maintained. On higher ground, 900 ft above sea level, with a more severe degree of exposure, as at Shothead Farm, Balerno, a belt width of 64 ft suffices within a comprehensive system of shelterbelts, although greater widths might be necessary for isolated belts in such an area. Where exposure is more severe, dwarfing and deformation of the trees may demand the employment of wider belts.

On upland areas, the optimum width of shelterbelts may be complicated by the economics of establishment and the natural desire to combine the provision of shelter with some form of productive forestry. Increased belt width implies a decreased degree of penetrability to the wind and a consequently reduced zone of shelter to leeward of the

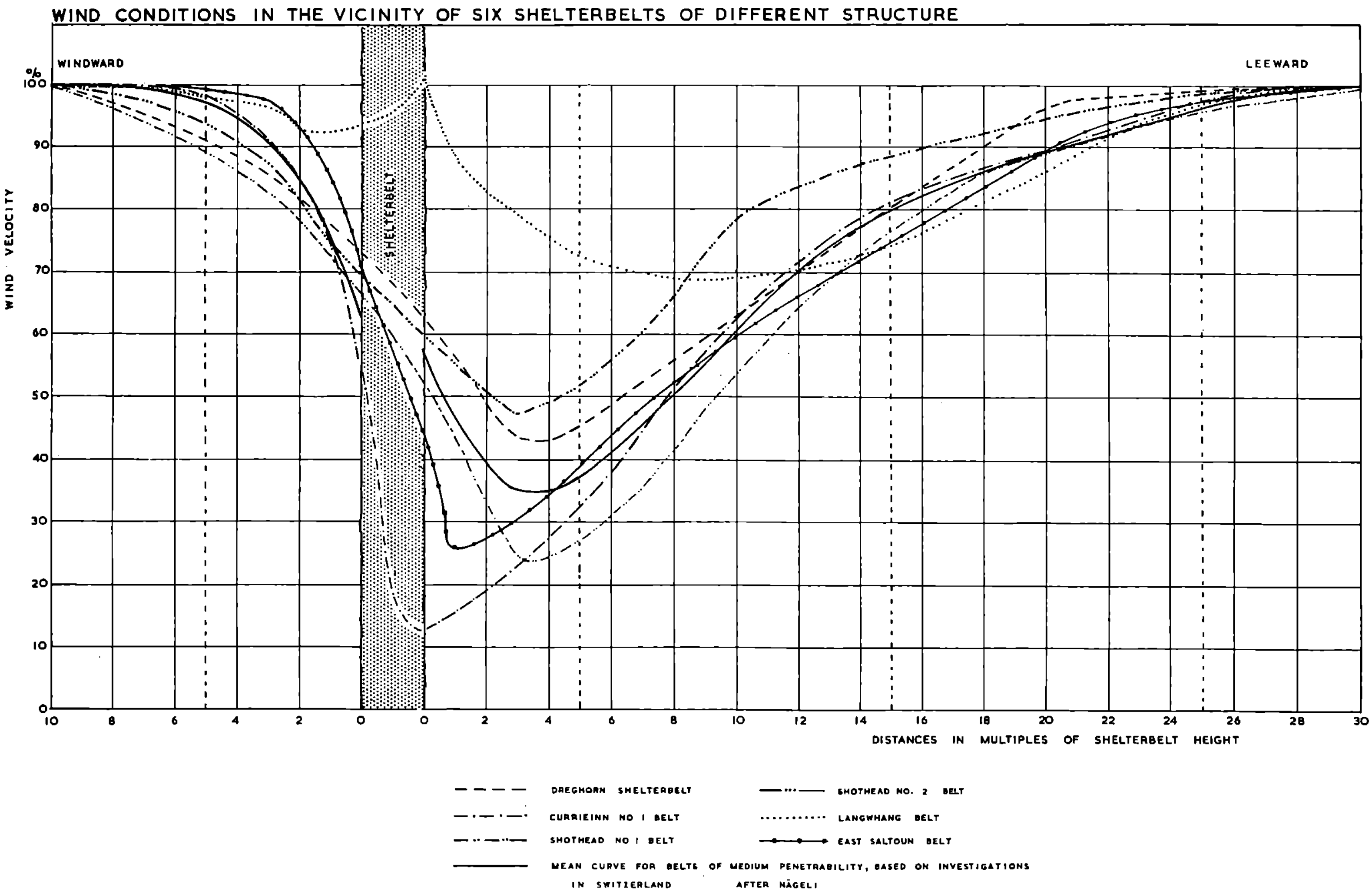


FIGURE 51. Wind conditions in the vicinity of six shelterbelts of different structure. Measured at 1.5m above ground and expressed in percentages of the free-wind speeds.

belt. The wind-tunnel investigations indicate that the width/height ratio in shelterbelts has a significant effect in determining the extent and nature of the sheltered area in their vicinity, although this effect may not be apparent until the degree of penetrability falls below a critical value, estimated to be 20%. The value of the width/height ratio, above which the width of the belt becomes the limiting factor in determining the shelter effect, must depend on the structure, i.e. the penetrability, of the shelterbelt. Further investigations are necessary to discover the critical widths for belts of varying composition and structure. Above these critical widths, the belts lead the wind parallel to their upper surfaces with a resultant rapid downward transfer of energy after the wind leaves the leeward margins, thereby restricting the extent of the leeward eddy zone and promoting the resumption of the unobstructed wind velocity comparatively close to the belts.

It is obvious that the optimum width is dependent on the stage of development and height of the belt. In the case of wide shelterbelts the relative efficiency must increase with height growth, i.e. as the width/height ratio decreases, whilst at the same time the degree of penetrability will be increased usually by thinning operations. It may be expected, therefore, that wide belts will exhibit a low efficiency index in their early years and one much smaller than narrow belts of similar age and height. It may be assumed that pure coniferous belts of more than 2½ chains in width, planted at the conventional spacing, will be excessively dense in their youth and fall below the critical degree of penetrability. This is evident from the general density exhibited by the Currieinn belts at 25-30 years, although subsequent thinnings may improve their efficiency.

Regarding the external form of shelterbelts or their cross-sectional profiles, the wind-tunnel investigations, supported by the field studies of the Gosford coastal shelterbelt, suggest that belts with sloping crown surfaces should be avoided where practicable since they afford a restricted leeward zone of shelter near the ground. Gradients on windward margins are particularly undesirable. This would appear to be confirmed by the fact that in exposed regions the natural effect of the wind is to minimise any resistance to its normal flow pattern. Thus, on exposed seaboards, as at Gosford, severe wind-pruning occurs until a more or less aerofoil surface is produced and resistance reduced as far as possible. In very exposed situations it is evident that the formation of a windward slope cannot be avoided entirely but it can be restricted by the use of artificial screens to promote establishment of the belt and by the careful selection of the most resistant tree and shrub species for the windward margin. It may be noted here that in the Gosford belt the variation in the height of the windward wall has not determined the degree of slope in the crown surface but merely the effective height of the canopy above ground level at both windward and leeward edges.

In effect a gradient on the windward margin of a shelterbelt is similar to an increase in overall width and restricts the extent of the sheltered zone to a degree dependent upon the acuteness of the angle of slope. The inclination of the windward edge causes deflection of the major part of the air stream over the top of the belt, thus reducing the effective degree of penetrability to the wind. The more shallow the gradient, the more complete is the deflection of the air stream over the belt.

For this reason shelterbelts with vertical windward and leeward borders are generally more efficient in reducing wind velocity than designs with various combinations of windward and leeward slopes. Except in very exposed districts they will be more easily established and managed than belt types requiring specific slopes in the crown canopy. These findings are at variance with current American recommendations: Bates (1934) suggested the streamlining of belts so that in cross-section they appear as a gabled roof with a wide sweep at the eaves, to be achieved by planting central rows of the main tree species, flanked on either side by smaller trees and shrubs. As a result of wind-tunnel studies of several designs of windbreak, Woodruff and Zingg (1953) supported the conventional 10-row pattern for American conditions with maximum height attained in the 7th row (Fig. 11, C). However in their investigations, none of the designs studied has been compared with a 10-row model having vertical windward and leeward edges.

Applying this evidence to practice, it would appear that every effort should be made to obtain the maximum belt height as near as possible to the margin, thus giving an abrupt rise from ground level to the crown canopy and allowing the belt to act as a moderately penetrable barrier rather than an obstruction to be by-passed by the wind. This can best be obtained by the judicious use of shrubs and minor tree species occupying the space below the crowns of the main tree species and preventing overhanging of the latter into adjoining fields. The windward margin of the East Saltoun shelterbelt (Plate 19) illustrates the possibilities in this direction.

Regarding the upper canopy surface in a shelterbelt, there is no evidence at the present time as to whether a smooth horizontal surface is desirable or an irregular canopy more suitable. It is possible that an irregular crown surface, causing a series of small eddies above the belt instead of immediately to leeward as found with the uniform design, may protect more efficiently the ground down-wind of the belt. Wind-tunnel investigations of a group structure model (p. 83) show that no reverse flow conditions are produced at any elevation with groups extending over a width of five times the model height. It would seem that shelterbelts of group structure warrant more detailed investigation. From a practical point of view, economic considerations generally require that shelter be provided as quickly as possible after planting. In order to achieve this it may be necessary to use temporary species affording rapid height growth to give the desired height to the belt, allowing the permanent species to develop more slowly and provide protection at lower levels. Whether the temporary species should be planted in groups or scattered individually throughout the belt must depend on the species and locality factors but such a pattern promises a sound basis for the future management of the structure, and, therefore, merits attention. During the early life of such a shelterbelt an irregular canopy will be inevitable; it requires to be demonstrated whether this is advantageous or otherwise from a protective aspect.

Little information is available regarding the shape, in plan, of shelterbelt boundaries. Departures from the customary straight margins are likely to be considered only where shelter is required for stock on open hill grazings. The evidence from gale damage to forests suggests that re-entrants should be avoided on margins since they are particularly vulnerable at the apex of such "wedges" and consequently more difficult to manage. Straight margins appear to be more resistant to wind injury and it may be assumed that this would apply similarly to shelterbelts. Small shelter plantations on upland areas are not required usually to provide shelter except within their immediate vicinity, their main function being to shelter stock against occasional severe weather. Their design must cater therefore for periodic necessity rather than continuous use and be adapted accordingly to comply with local storm and topographical conditions. In this specialised sphere of shelter planting no general conclusions can be drawn regarding suitable plans for belt shapes.

The initial design of a shelterbelt should form the basis for the establishment and development of the ideal belt structure for a particular set of climatic and edaphic conditions. Information regarding ideal belt structures, their establishment, development and maintenance, can be obtained from prolonged and detailed study of existing shelterbelts of varying width, general design and composition.

Structure of Shelterbelts

The extent and nature of the sheltered area in the vicinity of a shelterbelt is mainly a function of the height of the belt and its degree of penetrability to the wind and, hence, its structural composition from the ground to crown level. Although prolonged and detailed study is necessary for the determination of the ideal structures which will afford maximum protective efficiency, certain general indications are revealed in the results of the present field investigations.

Relative wind velocities recorded in the neighbourhood of six belts of different structure are compared in Fig. 51 and Table 7. The Braidwood belt has been excluded because topography complicated study of the effect of belt structure on the wind flow pattern. Similarly, the rather specialised adaptation to environment portrayed by the Gosford belt prevents its consideration from a structural aspect, the main feature of this belt being its external form. The characteristic effect of each of the remaining six belts on the local wind regime is apparent from the course of the respective smoothed curves of wind abatement. In these curves, irregularities in the observed values attributable to known influences other than the overall structure of the particular belt have been levelled out for simplification of the comparative assessment of their efficiency. Thus, in the case of the Dreghorn belt, the sheltering effect of the stone dyke on the leeward margin and, likewise, the acceleration of the wind observed within the Shothead belts have not been shown, although these minor features must be considered in the assessment of general effectiveness.

From these results it can be confirmed that the more impenetrable the shelterbelt to the wind the nearer to the leeward margin of the belt is the minimum velocity obtained and as penetrability increases the minimum tends to move farther from the belt. The two extreme examples of this are the dense Currieinn No. 1 belt, where the minimum point of the curve is found at the leeward margin, and the very open Langwhang belt, where the minimum is not attained until 10h leeward of the belt. It is evident that the degree of penetrability of the six belts increases from dense to very open in the following order:

1. Currieinn No. 1 belt
2. East Saltoun belt
3. Shothead No. 1 belt
4. Dreghorn belt
5. Shothead No. 2 belt
6. Langwhang belt

In spite of its density the Currieinn belt exhibits a remarkably favourable distance protection although turbulence in its lee must reduce the general efficiency of the structure and, accordingly, it should be classified as slightly too dense. The order of density suggests that the East Saltoun, Shothead No. 1 and Dreghorn belts approach most nearly to the desirable moderate penetrability, which has been shown in earlier research to be most effective in providing shelter. When the penetrability exceeds the optimum degree, as in the case of the Shothead No. 2 and Langwhang belts, not only is the wind speed reduction less and the minimum wind speed further from the belt but also an acceleration of the wind is found within the shelterbelt itself or on the leeward margin. Such increased velocities, however, may be local in occurrence and may not determine the general course of the shelter effect, except in the very immediate vicinity of the belt margins, provided the belt is not too open throughout its height. This is evident in the case of the Shothead No. 1 belt, which, although registering a somewhat lower degree of overall penetrability to the wind than the Dreghorn belt, presumably on account of its greater width and higher density of stems per acre, nevertheless causes pronounced acceleration of the wind within the belt, thus reducing its general efficiency. Yet the curve of relative wind velocity indicates a high degree of sheltering efficiency except within the belt and close to the margins.

Analysing this evidence, it is clear that the acceleration of the wind in this case arises from the condition of the windward margin. The Dreghorn belt, with its less permeable windward margin formed by the hawthorn hedgerow but more open structure in the centre of the belt, shows no similar increase of wind velocity. The Shothead No. 1 belt, with only scattered hawthorn bushes on the exposed margin and no underwood to compensate for this deficiency, causes the wind to sweep through the belt near ground level. However, the leeward velocity reduction demonstrates also that the effect of an open margin near the ground can be quickly eliminated by, or at least subordinated to, the sheltering influence of the structure throughout the rest of the belt height. In the Shothead No. 1 belt side branches on the edge trees form a latticed screen within a few feet from the ground (Plate 16).

On the other hand, the absence of a close windward margin can have a pronounced effect on the leeward sheltered area if not counter-balanced by low branching in the trees or by undergrowth within the belt. This is revealed by comparison of wind abatement in the case of the Dreghorn and Shothead No. 2 belts. With similar widths and stocking densities, the main difference between these two belts is the hedgerow along the windward border of the former (cf. Plates 10 and 17).

From a practical point of view, a sudden acceleration of the wind close to and within the shelterbelt will have a detrimental effect on the stand microclimate, its soil and vegetation, with consequent complications in management and silvicultural treatment. Apart from possible decrease in sheltering efficiency, an open windward margin is undesirable in shelterbelts.

Considering the three belts, East Saltoun, Dreghorn and Shothead No. 1, all exhibit a fairly high degree of effectiveness. However, the wind abatement achieved by the Dreghorn belt is not as high as might be desirable since the velocity never falls below 40% of its unobstructed value, discounting the effect of the leeward wall. Therefore, it may be assumed that this belt is somewhat more penetrable than the optimum. Had the belt been of ideal density it is doubtful whether the presence of the stone dyke on the leeward edge would have produced a noticeable effect on the wind speed.

The East Saltoun belt, from the general trend of the respective curve, with its minimum at 1h from the belt, would appear to act in the manner of a rather dense belt. However, the degree of leeward shelter afforded is somewhat higher than the mean, not the ideal, wind reduction determined from the study of a series of moderately penetrable shelterbelts in Switzerland (Nägeli 1946). The East Saltoun belt is at present in an early stage of development, no brashing or pruning having been conducted, and branches extend far down the stems. Coupled with the close, and relatively high, overgrown hedge on the eastern margin (the windward margin during the investigations), the branches form a screen of low penetrability. As the belt height increases it is anticipated that artificial pruning will be necessary and the belt will then become more permeable in the trunk space. In this event the minimum point of the curve will tend to move farther from the leeward edge, although its percentage value may be increased slightly. It is highly probable that wind abatement at that stage will correspond closely with Nägeli's mean curve.

In the smoothed curve values of wind reduction, the Shothead No. 1 belt appears to afford the most efficient degree of shelter except for the increased wind speeds on the edges and within the belt. The distance protection exhibited by this belt is high. Comparing the course of this curve with the average for the Swiss moderate penetrability class (Fig. 7), the Shothead No. 1 belt is potentially of ideal structure as regards sheltering effect. It corresponds very closely in sheltering effect with the Epinette shelterbelt and the Riedthof old spruce belt (Fig. 19) as described by Nägeli (1946). An improvement in the windward margin, designed to obviate acceleration of the wind within the belt, would incur a slight decrease in overall penetrability, thereby reducing distance protection. It is likely that the belt would still be nearer the ideal than the mean for this penetrability group.

It is apparent that, of the belts studied, the East Saltoun belt must be adjudged to be presently and potentially the most effective in providing shelter. The results of the field studies demonstrate clearly that certain belts may afford a high degree of shelter and yet be in a transitional stage as regards development and general silvicultural condition. This is evident especially in the case of the Currieinn belt. Here the gradient of wind velocity resumption is more gradual than might have been expected from the general density of the belt (cf. Fig. 7), although a turbulent zone occurs up to 5h on the leeward side. The minimum wind speed is now found at the leeward edge or possibly within the belt itself. From the unthinned state of the shelterbelt it is unlikely that the present efficiency can be maintained indefinitely without careful treatment aimed at preserving the stand. Similarly, the Dreghorn and Shothead belts have reached a stage when regeneration of the stands must be considered, being at the peak of their efficiency with present stocking. It follows that an important feature of any belt structure should be its elasticity, i.e. its ability to be regulated periodically to preserve its efficiency and silvicultural condition. The field studies also indicate the importance of the windward margin in any belt structure.

The field investigations provide a general guide to the ultimate selection of ideal belt structures appropriate for particular sites. The Dreghorn, Shothead No. 1, East Saltoun and Currieinn belts are examples of the range in which such ideal structures may be found. Although exploratory, the present field investigations suggest a possible method for the determination of optimum structures, i.e. on the basis of their effect on wind velocity abatement in conjunction with consideration of their present and potential silvicultural condition. Further microclimatic investigations would require to concentrate attention on a wide variety of belt types within the above-mentioned range with the object of obtaining detailed information on the establishment and maintenance of belt structures.

Maintenance of Shelterbelts

With the high cost of establishing shelterbelts, it is obviously desirable that they should afford the maximum sheltering efficiency. Much of the adverse criticism of shelterbelts in the past may be attributed to their ineffectiveness in providing the required protection from wind and weather, due frequently to unsuitable selection of tree and shrub species in the first instance but more particularly to continued neglect and gradual deterioration. The proportion of poor and degraded belts throughout Britain is regrettably high and far in excess of the number which may be considered effective at the present time. In addition, many shelterbelts which now contribute reasonably adequate shelter to their adjacent areas show signs of approaching decline which should be checked by silvicultural intervention. Continuity of shelter is necessary from both economic and practical viewpoints and methods of treatment and management must be devised accordingly. In order to improve the efficiency of presently degraded belts and to maintain a high standard in serviceable belts a simple method of assessing the protective function of a shelterbelt is required. On the basis of such an assessment and a brief examination of site characteristics, stand structure and composition, appropriate silvicultural treatment could be decided with a view to regulating and controlling the belt's efficiency.

The fundamental purpose of a shelterbelt is the abatement of wind velocity and the associated influences which a belt exerts on microclimatic factors in its vicinity must be considered secondary. It would seem reasonable, therefore, to adopt wind velocity reduction as the criterion of usefulness of a shelterbelt. The field investigations described earlier have shown the characteristic effect of different shelterbelts on the wind regime. As a result it has been possible to discuss the efficiency of the various structures in terms of wind abatement and to compare their effectiveness with that of agricultural belts in Switzerland. Until detailed studies of several belts in Britain become available it will be convenient to adopt the mean values of wind velocity reduction, calculated by Nägeli (1946) for Swiss shelterbelts of the medium penetrability class, as a standard or yardstick for measuring the efficiency of British shelterbelts (see Figs. 7 and 51).

The application of a technique for assessment of the protective efficiency of a shelterbelt requires the study of wind conditions in the vicinity of each belt. Ideally, this implies wind-speed measurement over a distance of 40 times the height of the belt, a measurement line being laid out normal to the axis of the belt or parallel with the wind direction, whichever is more convenient, commencing at 10h windward and extending to 30h leeward of the belt. With the recorded velocity values obtained along this line expressed in relation to the unobstructed wind speed at the same height above ground and plotted graphically against a distance scale in multiples of shelterbelt height, the curve of velocity abatement can then be compared with the standard curve. The departure of observed velocity conditions from the standard can be interpreted in terms of silvicultural treatment needed.

The three important features of the curves shown in Figs. 7, 19 and 51 are the point at which the minimum velocity occurs, the relative value of the minimum and the gradient of velocity resumption after the minimum point. When the minimum is in the region of 30% or less and occurs within 2 heights from the belt, as with dense and very dense belts, the gradient of velocity resumption is steep. Such belts require to be made more penetrable to the wind. Where the velocity minimum is more than 40%, the minimum point tends to move farther from the belt the more open the structure and the gradient is shallow. These belts require to be made less penetrable until the minimum velocity is 30-40% and occurs between 3 and 5 heights from the shelterbelt.

Illustrating with an example from the field investigations described, the penetrability of the Langwhang shelterbelt is much greater than desirable. The minimum velocity recorded is only 69% of the free wind and occurs at 10 heights from the leeward margin. The stocking of this belt should therefore be increased until a minimum point of 30-40% is obtained nearer the belt.

Similarly, the curves of velocity reduction in respect of the Dreghorn and Shothead No. 2 belts demonstrate the extent to which their respective structures should be rendered less penetrable, whilst the Shothead No. 1 belt could apparently afford to be thinned slightly in the upper canopy without suffering any significant decrease in sheltering efficiency.

Further instances from the Swiss shelterbelts described earlier (p.39) may be mentioned. The Furthtal leaf-tree belt is more penetrable in winter than the optimum (Fig. 19), the minimum velocity attained exceeding 60% of the open-ground wind. This implies that efficiency could be increased by the introduction of a proportion of evergreen species, either leaf-tree or coniferous, into the belt or by establishing margins of such species. Examination of the belt on the spot must dictate the silvicultural measures to be adopted.

The young spruce shelterbelt at Riedthof appears somewhat dense in summer, with a correspondingly shorter extent of shelter effect; its efficiency is higher in winter. This is due to the fact that a dense growth of naturally-sown shrub and small tree species on the margins causes the belt to be virtually impenetrable near ground level during the summer. Examination of the belt reveals evidence of approaching deterioration in the spruce and the immediate treatment decided upon and already commenced in 1954 has been the gradual replacement of the spruce by poplars in a series of small groups widely spaced, utilising the natural growth to maintain the structure of the belt near the ground. As removal of the spruce proceeds, further periodic wind measurements should indicate whether more conifers are required on the windward margin for preservation of the optimum penetrability throughout the winter.

Again, the graph for the Epinette shelterbelt shows that this wide belt is more effective than the average for the medium class (Nägeli 1943, 1946). Thus, its penetrability can be reduced slightly without seriously affecting its efficiency. In this way regeneration technique can be applied gradually and frequent wind studies would suggest the desired intensity of regeneration fellings amongst the mature trees. In order to maintain the shelter to adjoining fields, silvicultural methods must be adapted with that aim in view and therefore require to be somewhat elastic. Regeneration operations will be rather specialised since microclimates and, probably more important, illumination conditions in shelterbelts are likely to differ considerably from those encountered in the forest.

It would appear that the maintenance of shelterbelt structure requires co-ordination of microclimatological study and silvicultural technique. Periodic investigations of wind conditions and sheltering efficiency are necessary to ensure that the maximum value is being obtained from the shelterbelts.

Reducing the field procedure to practice, it may be possible only rarely to make detailed velocity measurements at several points within the vicinity of a belt. In order to reduce the number of observation points and apparatus to a minimum, it may be sufficient to conduct wind speed measurements at five points only:

- (i) in the open, beyond the influence of the belt or other sheltering obstacle, so as to obtain a value for the free wind speed;
- (ii) at the windward edge of the belt;
- (iii) at the leeward margin of the belt;
- (iv) at the minimum velocity point: in a strong wind this can be located fairly accurately by walking against the wind, otherwise it must be found by experimentation;
- (v) at a point approximately 15 heights to leeward of the belt. These five points will give the general course of velocity abatement and further points may be interpolated within the limits of accuracy required.

As further evidence is accumulated from the study of different shelterbelts more information will be forthcoming regarding suitable structures for various localities and silvicultural treatment may be able to be prescribed in more detail. In the initial stages of rehabilitation of degraded belts and the maintenance of presently efficient shelterbelts, however, it would seem that this simple index of shelterbelt efficiency, based on a few observations of wind velocity reduction, offers a "rule-of-thumb" method for enhancing the benefits and economic value of shelterbelts.

Chapter 12

MODIFICATION OF WIND CONDITIONS IN RELATION TO THE SITING OF SHELTERBELTS

THE STRATEGIC SITING of shelterbelts in regions of irregular topography is of primary importance if maximum protective efficiency is to be obtained from the belts. Intensive study of air flow pattern near the ground in upland areas would be necessary for general conclusions applicable to the siting of belts. The diversity of meteorological and topographic conditions in such regions must inevitably limit the practicability of detailed investigation of wind conditions, except where the findings are destined for local application.

However, it would appear that meteorological evidence obtained in the course of research in connexion with aviation and lee-wave formation (Corby 1955) and the development of wind-power sites for electricity generation (Putnam 1948; Golding and Stodhart 1949, 1952) can contribute considerable information of practical value to the agriculturist and forester concerned with the flow of wind near the ground in hill and mountain regions.

In the matter of siting shelterbelts, wind behaviour over ridges and isolated hills requires clarification, in order to appreciate the position at which a shelterbelt might be expected to be most efficient.

Local evidence and knowledge would seem to be the final basis of site selection for a proposed belt, in conjunction with theoretical considerations, as available. In hilly territory it is evident that the prevailing wind direction can change within short distances, due to deflection by the topography. In the case of the Dreghorn shelterbelt at the extreme north end of the Pentland Hill range, the prevailing wind has been observed to be locally westerly (p. 000); one mile to the north or west the prevailing wind is south-westerly. Similarly, a westerly wind has been found to prevail towards the mouth of Boghall Glen, formed in the Pentlands by Caerketton, Woodhouselee and Allermuir Hills (National Grid map reference NT 240653), whilst at the head of the glen wind direction is extremely varied and where the glen emerges on the south-east slopes of the Pentland range the prevailing direction from the Esk Valley is south-westerly. In exposed areas the prevailing wind can be ascertained frequently from the vegetation. The character of deformation in vegetation may also be used as a quantitative indication of local exposure to wind, although such evidence must be adjudged approximate owing to genetical variation in plant material and probable changes in soil conditions.

Previous research has established that shelterbelts should follow local topographic changes such as spurs and ridges. Where the wind is funnelled along a valley it is customary for belts on the slopes to be orientated against the contour, taking advantage of any slight fold or ridge in the general direction of the gradient. The belts are generally situated on the crests of such folds or ridges. This practice is obviously desirable since it has been shown in the case of the Braidwood belt (p. 109), situated on a slight leeward slope produced by a glacial drift mound (Plate 23), that the wind can overflow belts in such a situation. With a reversed wind direction, higher ground to leeward of a shelterbelt can also cause a restricted zone of shelter. The policy of siting belts on the crests of such small ridges is in agreement with the research results of Blenk (1952), who suggested that shelterbelts are more effective at the top of ridges or on the windward side. However, such a rule is of limited application and, although apparently suitable for minor spurs and ridges where the wind is flowing more or less horizontally along the prevailing contour and no significant speeding-up of the stream is produced by this minor change in the topography, it is unlikely to obtain similarly in the case of larger ridges lying athwart the wind direction.

Leeward slopes below 8° are assumed to be unprotected (Woelfle 1950) and it has been suggested also that the sheltered zone behind the summit of a hill is restricted to a short distance, according to the steepness of the slope, and is followed by a region with increased wind speeds (Woelfle 1937). Putnam (1948) found that the greater the height of a ridge in relation to the width of the base of its cross-section, the greater was the speed-up factor of the wind over the crest. However, a sharp ridge caused considerable turbulence on the leeward side. It would appear, therefore, that belts should be situated beyond the disturbed area produced by the ridge and, thus, where normal direction is restored and the wind begins to resume velocity. The location of the belt must vary according to the height of the ridge and its horizontal extension parallel with the wind direction.

With a long ridge normal to the wind direction, the increase in speed arises from compression of the streamlines over the crest; a similar increase is also attained over an isolated hill because much of the flow at low levels passes around the hill and accordingly the crest-level flow is derived from a higher level (Corby 1955). From this it may be inferred that belts on windward slopes of isolated hills may suffer a restriction of their shelter effect due to the fact that the incident wind may not be parallel with the gradient. The steeper the slope the less effective must be a contour belt on the windward face. Belts on the flanks of isolated hills must allow for the considerably higher velocities to be found there.

Some degree of natural protection close to the ground is to be observed on some of the typically rounded hills of the Southern Uplands, especially where the slope begins frequently to flatten out towards the summit. A very slight decrease in the degree of slope, not easily perceptible to the naked eye, may cause upward deflection of the wind or the direction of the latter may have been conditioned by the slope lower down the hill, resulting in a small zone above ground, often no more than 2-3 ft in height, becoming comparatively sheltered. This has been noticed particularly on the Sell Moor at Stow, Midlothian (National Grid map reference NT 478442), where sheep frequently congregate on the windward (south-western) slope above 1,250 ft.

A further consideration in connexion with shelterbelt layout on upland areas must be drifting of snow in winter and possible danger to sheltering stock. It is suggested that the edges of naturally sheltered areas, such as hollows and corries, should be rejected as potential sites for belts. As far as possible shelterbelts should be placed on reasonably uniform ground and in exposed situations to prevent accumulation of snow in their lee. It would appear that belts which follow the gradient are preferable to contour belts during severe winters. General information concerning siting can be obtained frequently from the observation of old stone stells on sheep grazings. Where such stells have been erected in valleys they are usually located on any small patch of ground above the general level of the valley floor to minimise the danger of being buried in snow drifts.

In conclusion, there is evidently a need for further information designed for general guidance in the layout of shelterbelts in upland regions, although in the final stage of site selection each area must be assessed on its individual character. Exploratory investigations have indicated that measurement of wind velocities conducted in the field at 1.5m above ground are liable to considerable error, introduced by very slight topographic changes, and allow insufficient information on the pattern of air flow over hills. It would seem also that knowledge of stability conditions in the airstream would be desirable for comparative evaluation of any field data obtained from short-term observations.

Chapter 13

SHELTERBELT TECHNIQUE IN FORESTRY PRACTICE

THE APPLICATION of shelterbelts to forestry practice must be considered from two fundamentally different aspects; firstly, provision of continuous shelter near the ground with a view to assisting cultural operations and, secondly, safeguarding the forest against damage by occasional, severe winds. The first aspect concerns mainly the initial shelter desirable on exposed areas scheduled for afforestation and within regeneration coupes in the forest. The second objective comprises protective margins and internal wind-firm strips in the established forest to ensure stability of the stand. In addition to the latter function, margins should be so designed as to enhance stand microclimate and promote the general condition of the forest.

Shelterbelts designed to provide shelter near the ground and, consequently, an amelioration of the microclimate in their vicinity require to be moderately penetrable to the wind, acting as a filter to the wind rather than an obstruction and producing a series of minor eddies which form the basis of shelter effect. In this respect the requirements of forest belts must be accepted as similar to those for agricultural shelterbelts. Layout, design and structure should follow therefore the general pattern previously discussed (see Part Three, Chapter 11).

On the other hand belts intended to protect the established forest, especially against severe gales, must aim at deflecting the wind and minimising any disturbance in the general flow pattern. In this case shelter is required at all levels from the ground to, and even beyond, the crown surface.

It is obvious that the two objectives cannot be separated entirely and that the belts established on open ground before afforestation is begun must be capable of forming the protective margins and internal wind-firm strips necessary in a later stage of development of the forest.

Regarding pre-afforestation shelterbelts, natural development of a sloping windward margin may be unavoidable in very exposed regions, a somewhat restricted zone of leeward shelter being incurred thereby, as shown in the investigations described earlier (p. 71 et seq.). This effect may be curtailed by careful selection of resistant species and the use of artificial screens to furnish initial shelter to the belts and encourage the trees and shrubs to reach the greatest possible height. In this way, a smooth canopy slope extending right to the ground may be avoided; a vertical margin only a few feet in height will allow the wind to permeate the belt instead of being deflected entirely over it. Also, the maximum height of the belt will be reached more quickly, i.e. nearer the windward edge, if it is recognised that the degree of slope caused by the exposure will remain the same irrespective of the artificial barrier height, as indicated by examination of the Gosford coastal shelterbelt (p. 113). Where a graded cross-sectional profile in the belt is inevitable, appropriate allowance for the shorter distance protection should be made in the espacement between belts.

The spacing between belts on a new area scheduled for afforestation should take into account the eventual height of the belts, their height at the time when the rest of the planting will be carried out and the fact that they will ultimately perform the second function of protection against storm damage. Doubtless, economic considerations will determine the delay between planting of the belts and the afforestation programme. An important criterion should be that the shelterbelts have had reasonable opportunity to adapt themselves to the wind, in so far as this is possible in their early stages of development.

It would appear that the maximum distance between parallel belts normal to the wind direction should be 25 times their height. Height in this case must be regarded as the optimum height to have been attained before the general planting proceeds and not as the final belt height. Thus, if afforestation commences when the shelterbelts are 15 ft high, it would be desirable to plant the belts not more than 125 yd apart. Transverse belts, intended to provide protection against strong winds other than the prevailing wind and not usually required to yield shelter until the main stand has reached a critical stage in height growth, could be planted at greater intervals. Experience has shown that little gale damage is to be expected in the first 25-30 years of the life of a coniferous stand (Andersen 1954); therefore, transverse belts parallel with the prevailing wind direction could be laid out at distances equivalent to 25 times their estimated height at the time when the general planting is 25-30 years of age, bearing in mind the fact that earlier writers have suggested the desirability of dividing a forest area into small units of 5-10 acres by means of such internal wind-firm strips.

Shelterbelts formed by severance fellings to protect regeneration areas within the forest should also be moderately penetrable to the wind, particularly since the greatest potential danger in the sheltered region is likely to be frost. Stagnation of the enclosed air must be avoided. A further consideration would appear to be that these narrow strips may not be adapted to withstand sudden exposure to wind.

Protective margins are required to prevent mechanical injury to the stand and also the detrimental, physiological effects of wind and sun. Since wind exerts a desiccating influence on plant material and affects adversely stand microclimate and soil conditions, whilst insolation hastens decomposition of organic matter, admits undesirable ground vegetation and renders conditions unfavourable for natural seeding and regeneration, protective margins should be fairly impenetrable to wind and sun. From the aspect of shelter against storm and mechanical damage, the chief consideration must be the pattern of air flow over a forest. A vertical margin, giving rise to a sharp upward deflection of the wind stream, may cause serious turbulence and consequent wind-blow some distance behind the edge of the forest during a gale. Fritzsche (1933) records that a gradual transition from field to forest, as provided by a sloping canopy, probably involves less turbulence and accordingly less danger of damage in the interior of the stand; an example where top-cutting of the edge-trees has afforded protection to the stand behind is quoted. Wagner (1923) has stressed also the fact that a vertical velocity component, together with the turbulent effect of the tree crowns, may increase danger to the forest downwind of the margin. This evidence favours very strongly a sloping windward margin, which is confirmed by the results of the wind-tunnel investigations described earlier (p. 71).

In the present research a gradient on the windward margin has been found to deflect the major part of the air stream over the top of a belt or plantation, at the same time reducing the effective degree of penetrability of the margin. The more shallow the gradient, the more complete is the deflection of the stream over the belt. Models of such construction showed that, the more acute the angle of the windward edge, the smaller was the zone of disturbed flow to leeward and the shorter in extent the leeward sheltered area (Figs. 24-36).

From this evidence it may be deduced that a sloping windward margin is desirable from the aspect of protection against storm damage. The width of such a graded margin must depend on the degree of exposure and resultant natural slope produced in the canopy. Where continuous exposure alone is unlikely to produce a natural gradient on the margin, this can be derived artificially by means of suitable selection of tree and shrub species of different potential height growth and appropriate arrangement of the planting pattern. Even in very exposed situations protective margins should not require to occupy more than 150-200 ft in width; this is evident from the Gosford shelterbelt.

The influence of the structure of the forest on wind damage is not clear. Woelfle (1936-7) has suggested that individual trees, groups and stands that reach above an otherwise uniform canopy are apt to be damaged. On the other hand, it is probable that an irregular canopy, by producing a series of small whirls and eddies immediately above the crowns which act as "roller bearings", may maintain the force of the wind along a level some distance above the crowns and thereby reduce the danger to the stand. It would follow that there would be a critical size for such eddies and, consequently, an optimum size for circular clearings and diameters of groups, if such a scheme of management were employed. Further investigations in this connexion would appear to be desirable.

Little information is available regarding the layout of plantation margins but it is apparent from earlier research evidence (Woelfle 1950) that margins should be kept fairly straight and re-entrants should be avoided since they form funnels for the wind, causing two deflected streams which meet at the apex of the wedge with a resultant pressure approximately equal to the square of the combined velocities. In upland areas forest boundaries should be laid out so as to exclude where possible natural channels which concentrate the wind streams; otherwise suitable allowance must be made in the selection of species for such situations. Irregularity of topography must complicate the layout of protective margins and few general conclusions can be drawn from observational evidence available. On steep windward slopes it would appear that the gradient itself offers a considerable amount of protection to a forest stand; damage to leeward slopes may arise from turbulence caused by the crest of a hill or ridge. In this respect, the relation of the height of a ridge to its horizontal extension in the path of the wind, as mentioned earlier (Part Three, Chapter 12), must play an important part.

The economic significance of forest protective margins and internal stabilising belts requires detailed consideration. On exposed areas it is evident that margins designed specifically for shelter could be contained within a smaller area than that frequently occupied by retarded and stunted growth when the main timber species is planted right to the edge of a forest block. Shelter would also permit the afforestation of areas considered at present to be too exposed for productive forestry. The employment of shelterbelts would introduce two distinct objects of management within the forest, which might be resolved by the provision of two working circles: protective and productive.

To summarise, it would appear that shelterbelts on areas scheduled for afforestation should be penetrable to the wind and follow the general pattern of agricultural belts, as far as is consistent with the prevailing degree of exposure. Protective margins of forests require to offer the minimum resistance to the normal flow pattern of the wind and, in this respect, a sloping crown surface to windward is desirable. If an adequate gradient is provided, allowing the wind to be deflected over the forest, the margin will be virtually impenetrable to the wind; this is desirable from the point of view of preserving a favourable microclimate within the stand.

Further research would appear to be necessary on the silvicultural implications of shelterbelts in forestry practice, on the effect of an irregular forest structure on the pattern of air flow over the forest and its resistance against wind damage, particularly in districts liable to severe gales, and also on the economic aspects of providing shelter to the forest in the form of protective margins and internal strips.

Chapter 14

SUMMARY AND CONCLUSIONS

1. Under terms of reference providing for study of the effects of shelterbelts on microclimate, particularly their effect on wind conditions, the immediate aim of the research has been the augmentation and utilisation of existing data of shelterbelt influences. Emphasis has been laid on the practical forestry aspect of shelterbelt technique, i.e. the establishment and maintenance of tree belts appropriate to the requirements of agriculture and productive forestry.

2. The research programme has been divided into laboratory and field investigations. Physical research on two fundamental problems of shelterbelt design, viz. the effects of windbreak width and cross-sectional profile on the formation of a leeward sheltered area, has been conducted, using model windbreaks in a wind-tunnel. Field research on the

influences of shelterbelts on the microclimates of their adjacent areas has concentrated on the assessment of the efficiency of a few selected belts in the vicinity of Edinburgh on the basis of their effect on wind abatement and their general structural and silvicultural condition. These studies have been exploratory investigations directed towards ultimate determination of optimum belt structures which are likely to afford maximum sheltering efficiency.

3. From wind-tunnel studies of shelterbelt width it has been concluded that the width/height ratio in windbreaks has a significant effect in determining the extent and nature of the sheltered zone down-wind, although this effect may not be apparent until the degree of penetrability of the windbreak falls below a critical value, estimated to be about 20 per cent. The value of this ratio, above which the width of windbreak becomes the limiting factor in determining shelter effect, has been found in these studies to be 5; this value may not be expected to be of general application in nature but must vary according to the open-ness of the belt structure.

Wide windbreaks tend to lead the wind parallel to their upper surfaces with a resultant rapid downward transfer of energy after the wind leaves the leeward edge. The eddy zone to leeward of wide windbreaks is reduced by the air flow over the top of the barriers to an extent dependent on their width. In consequence a more rapid resumption of the unobstructed wind velocity is possible and, accordingly, a decrease in distance protection results.

Further field investigations are desirable, if suitable areas can be found, to substantiate this evidence and to consider the quantitative translation of wind-tunnel studies to field research. In the meantime it is obvious that there is a maximum width of belt which should not be exceeded if maximum sheltering efficiency is to be ensured in the mature belt. Optimum widths are likely to vary with species, planting density, subsequent treatment and consequent degree of penetrability to the wind but should be obtained within limits imposed by principles of good forestry practice, e.g. it would be undesirable to allow a very open stocking in a shelterbelt, so as to maintain a moderate degree of permeability, if a similar penetrability could be obtained by means of a more narrow, adequately stocked and well managed belt. It must be concluded that, since the width/height ratio of a belt will decrease with height development until the final height is attained, wide belts will exhibit a relatively lower efficiency index in their early years and one much smaller than narrow belts of similar age and height.

4. Regarding cross-sectional profiles in shelterbelts, a gradient on the windward margin is similar in effect to an increase in width and restricts the extent of the leeward sheltered area to a degree dependent upon the acuteness of the angle of this gradient. An inclined windward edge causes deflection of the major part of the air stream over the top of the windbreak, thus reducing the effective degree of penetrability. The more shallow the gradient, the more pronounced is this reduction. Since the fundamental effect of a windward sloping canopy is to minimise any resistance to the normal flow pattern of the wind, this phenomenon is of advantage in connexion with marginal protection of forests. On the other hand, where shelter is required near the ground, belts with vertical windward and leeward edges are generally more effective in reducing wind velocity than designs involving various combinations of windward and leeward gradients. This is due to the fact that the former belt type causes more disturbance in the air flow, producing a series of light eddies and turbulent flow, which form the basis of shelter effect.

Laboratory findings on this aspect have been confirmed by field studies of a coastal shelterbelt with a degree of slope in the crown surface of approximately 10°. The unobstructed wind velocity at 1.5m above ground was resumed relatively quickly to leeward of the belt.

It may be concluded that shelterbelts with more or less abrupt margins, which allow the wind to filter through the belt, are more suitable in providing shelter near the ground than belts with graded tree-heights from windward to leeward and are more appropriate to agricultural requirements and for forest areas destined for afforestation or regeneration. However, for protection against wind damage in the established forest, margins inclined to windward are evidently more suitable.

5. Wind-tunnel experiments suggest that a cumulative shelter effect may be found behind a system of two parallel shelterbelts but the close spacing of the two belts necessary, together with the small degree of additional shelter obtained, is likely to render such an arrangement in the field impracticable. The field studies indicate that it is possible to ensure that at no point between two parallel belts planted sufficiently close together is the free-wind velocity obtained, although no cumulative effect may be visible behind the second barrier. If such systems are separated by a distance equal to 26 times the height of the more windward belt, the entire intervening area is sheltered to some extent and the unobstructed wind velocity does not occur between the two belts.

6. Preliminary investigations of a group structure shelterbelt show that no reverse flow conditions are produced to leeward of such a fairly wide wind-tunnel model. Such structures may be more effective with regard to the quality of the shelter produced

than uniform windbreaks of similar height and width but overall planting arrangement. Further investigation of such structures is desirable since it is possible that, with an irregular belt canopy, the formation of eddies above the belt, instead of immediately to leeward as with the conventional design of belt, may have a significant effect on the extent and degree of shelter produced to leeward. In connexion with the stability of forests during strong winds, more evidence is required of the effect of an irregular crown surface on air flow since it is probable that a succession of small eddies formed within and around groups of trees and within depressions in the canopy may act as "roller bearings" and cause the lifting of the concentrated flow above the crown level and thus prevent serious damage. Principles of group structure may be of major importance in regard to the establishment and maintenance of efficient shelterbelts.

7. The sheltering efficiency of a shelterbelt may be determined by the study of its effect on microclimate, particularly wind velocity abatement and reduction of evaporation rate. A simple method of estimating efficiency, based on a few observations of wind velocity at 1.5m above ground along a line normal to the axis of the shelterbelt and subsequent correlation with average values of wind reduction for belts of a particular penetrability class, has been outlined. Such a simple index of shelterbelt effectiveness offers a "rule-of-thumb" method for gauging treatment necessary from time to time to preserve the optimum degree of penetrability to the wind, e.g. intensity of thinning. The treatment prescribed must allow for continuity of sheltering efficiency and general well-being of the belt.

8. Continued study of the microclimatic effects and efficiency of existing shelterbelts will further the ultimate determination of suitable belt structures for different localities and particular functions. The field investigations of selected shelterbelts, carried out between 1953 and 1955, give general guidance on the ultimate selection of optimum structures. It is apparent that belts which are effective at present in reducing wind velocity may be in poor silvicultural condition and have reached the peak of their efficiency unless suitable treatment is applied promptly. The potential structure of a shelterbelt, the flexibility of its structure and its ability to be regulated are factors to be considered in the classification of efficient belts. The importance of a close windward margin in shelterbelts has been demonstrated.

Of the belts examined, the East Saltoun shelterbelt, 50 ft in width, composed of ash groups within a matrix of European larch and Scots pine and with a hawthorn hedge on the windward border, has been found to approach most nearly the optimum structure, in view of its present and potential efficiency.

9. Further information concerning the pattern of air flow in regions of irregular topography is desirable. Although wind conditions in such areas are extremely complex and their intensive study possibly of local value only, it may be concluded that general principles related to the siting of shelterbelts in upland regions, so that they display their maximum efficiency, can be forthcoming from investigation of the behaviour of wind over ridges and on slopes. Exploratory investigations suggest that occasional measurements of wind velocity at 1.5m above ground are liable to considerable error attributable to very small topographic changes and allow insufficient detail of wind relationships in these districts. Further study, at elevations somewhat greater than 1.5m, would be of more practical and scientific value. Knowledge of stability conditions in the air stream would appear desirable for comparable evaluation of any field data obtained from short-term observations. The final selection of shelterbelt sites must be decided in the light of such evidence available and from local information of wind conditions; observations of vegetation and animal behaviour may contribute in this respect.

10. Requirements of shelterbelts in forestry practice will be similar to those of arable farming where shelter is required near the ground, such as on areas scheduled for afforestation or regeneration. Such belts must form at a later stage the protective margins and internal wind-firm strips required in the established forest, where shelter is essential at all levels from the ground to the crown surface. Since the two requirements differ fundamentally, further detailed study of this question must be considered desirable. The present investigations suggest that the moderately penetrable shelterbelt is most suitable for protection near the ground whilst the virtually impenetrable, sloping, windward margin is most effective in minimising disturbance in the air flow and preventing wind damage behind the stand margin.

11. It may be concluded that future research on shelterbelts must, from the point of view of its practical application, be complementary to allied research, chiefly in agriculture. The requirements of shelterbelts, particularly in connexion with stock-rearing, have not yet been clearly defined by the agriculturist. A comprehensive scheme of research, embracing all interests, would seem desirable. Meteorology can contribute valuable information on the structure of the climate near the ground and, especially, on the pattern of air flow in regions of broken relief. It must be left to the agriculturist to pursue the question of the effects of microclimate on field crops and animal welfare in Great Britain and to

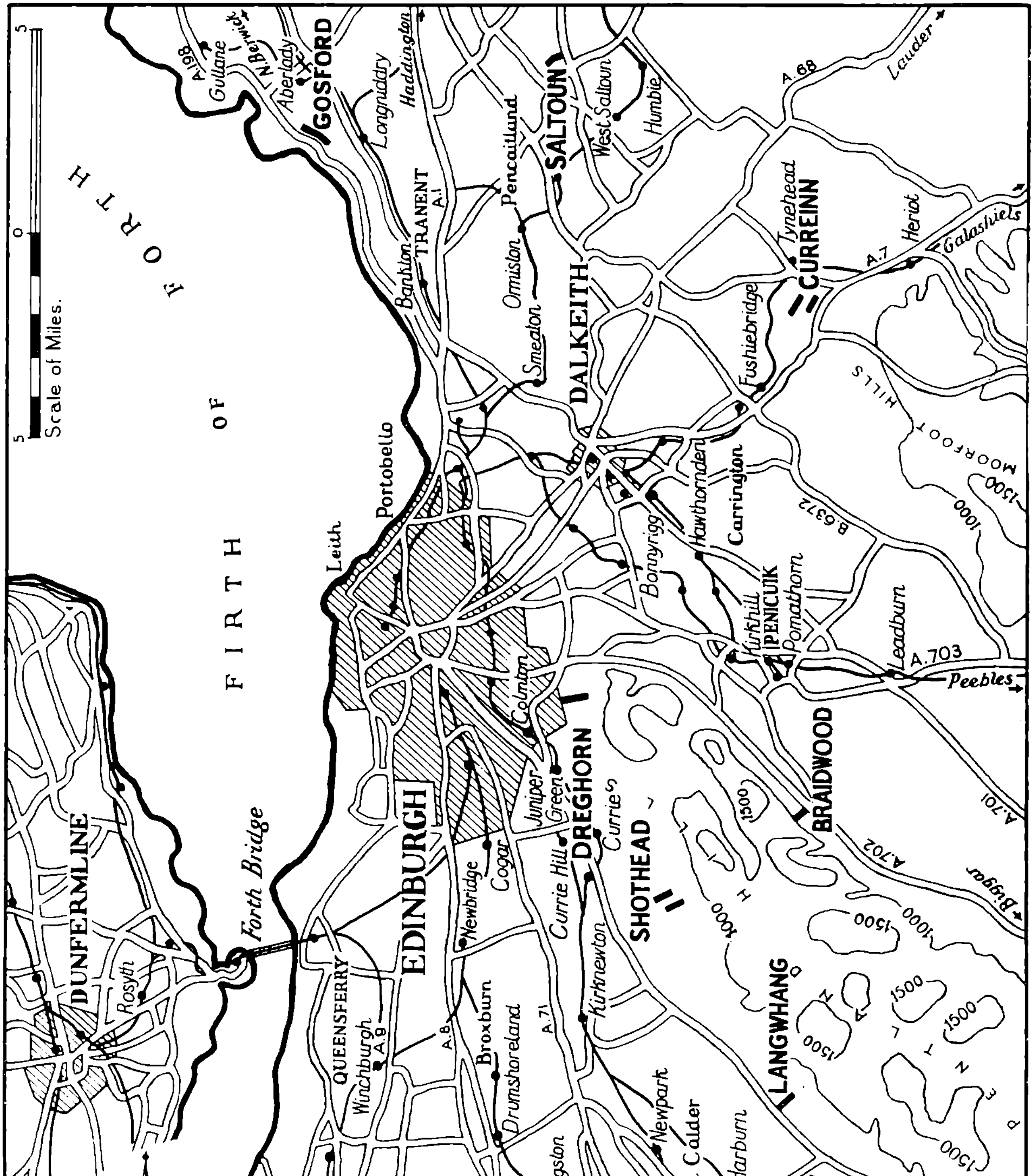


FIGURE 52. Map of the environs of Edinburgh, showing the situation of the several shelterbelts studied.

detail the requirements of shelterbelts for arable and stock-rearing areas. If, at the same time, forestry circles continue to investigate the influences of particular shelterbelts and the relation of shelterbelts to forestry practice, detailing the requirements in forestry, the forester can contract for the different requirements, aided by the appropriate meteorological and climatological evidence available. Finally, agricultural and forestry interests may collaborate in furnishing evidence concerning the economic value of shelterbelts, which information is most deficient at the present time.

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GLOSSARY OF TERMS, SYMBOLS AND ABBREVIATIONS

(Abbreviations of Journal titles in accordance with *World List of Scientific Periodicals*, 1900-1950, 3rd Edn., Butterworth's Scientific Publications, London, 1952.)

1. Terms:

Hedge — "A row of bushes or low trees (e.g. hawthorn and privet) planted closely to form a boundary between pieces of land or at the sides of a road; the usual form of fence in England. A barrier, limit, defence; a means of protection or defence". (*Oxford New English Dictionary.*)

Hedgerow — "A row of bushes forming a hedge, with the trees etc. growing in it; a line of hedge". (*O.E.D.*) Used to describe the single-row Danish shelter-strips but not wider belts of trees.

Latticed — The nearest English equivalent of a term used frequently in Russian shelterbelt literature to denote a shelterbelt of moderate penetrability throughout its height.

Shelterbelt — "A belt of trees serving as a protection against inclement weather; specifically in Forestry". (*O.E.D.*) "A natural or planted barrier of trees or shrubs for protection from wind and storm". (*Webster's New International Dictionary*, 1934.)

Width — Syn. "depth". Used exclusively herein to denote the horizontal dimension of a shelterbelt or model windbreak normal to its long axis, i.e. the distance through a belt or windbreak.

Windbreak — "Something, especially a row of trees, used to break the force of the wind, or serving as a protection against it". (*O.E.D.*) "A clump of trees or shrubs serving to break the force of the wind; hence any protective shelter from the wind, as a fence or the like". (*Webster.*)

2 Symbols and Abbreviations:

a	=	radius
d	=	diameter
h, H	=	height of screen, model windbreak or shelterbelt
Hg	=	mercury
p, p_o	=	pressure
q	=	velocity component
R	=	Reynolds' number
T	=	shear
u, U	=	velocity
v, V	=	velocity
x, X	=	abscissa (distance in direction of wind)
y, Y	=	ordinate
z, Z	=	height above datum, i.e. height above ground
z_o	=	roughness height
θ	=	temperature difference
μ	=	coefficient of viscosity
ν	=	kinematic viscosity
ρ	=	density of air
cm	=	centimetres
ft	=	feet
in.	=	inches
m	=	metres
m/sec	=	metres per second
mi	=	miles
mi/hr	=	miles per hour
min	=	minutes
yd	=	yards
B.H.Q.G.	=	Breast-height quarter girth

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