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SHELTERBELTS AND MICROCLIMATE

By

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

DEPARTMENT OF FORESTRY
EDINBURGH UNIVERSITY

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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, "agro-meteorological" 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

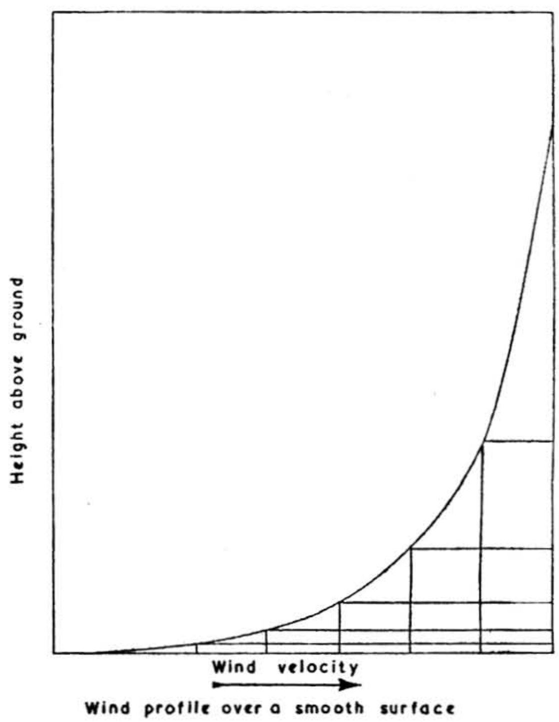

FIGURE 1. Wind profile over a smooth surface, illustrating the effect of frictional drag.

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

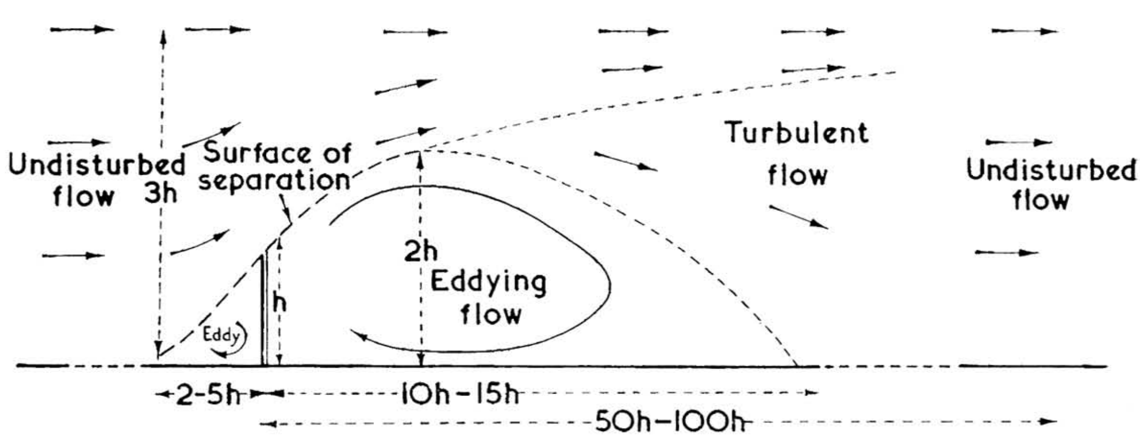

FIGURE 2. Some characteristics of the air-flow pattern due to a near-solid, cross-wind barrier (not to scale) (after Gloyne).

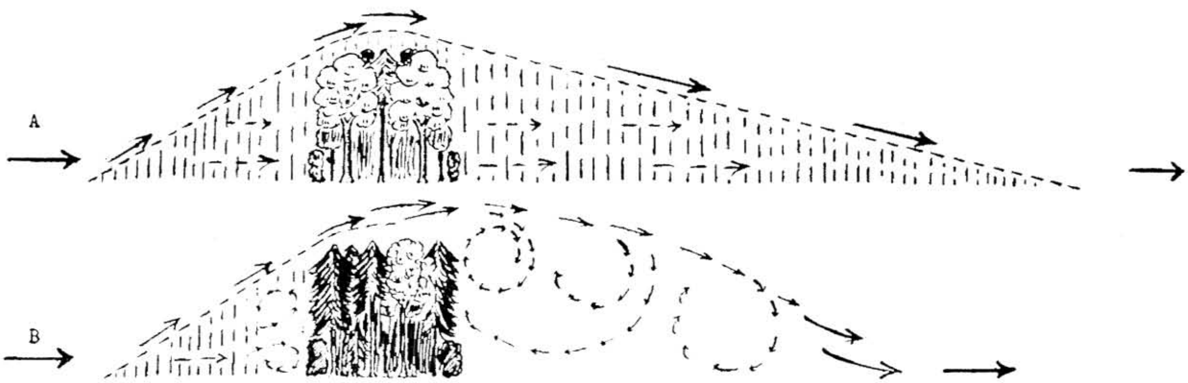

FIGURE 3. Flow of wind over (A) a moderately penetrable and (B) a dense shelterbelt.

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

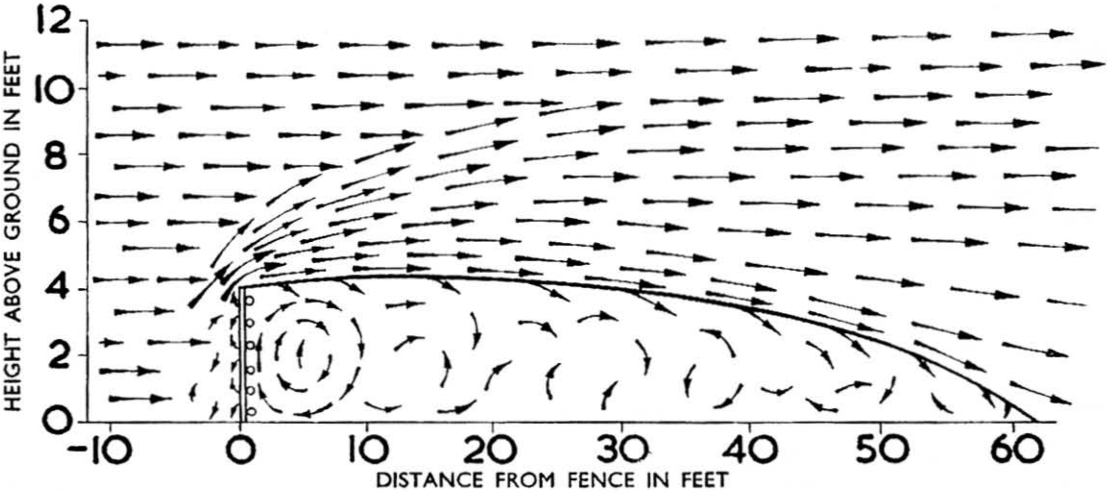

FIGURE 4a. Eddy area behind a permeable four foot high vertical slat fence, of 50 per cent density, (after Finney).

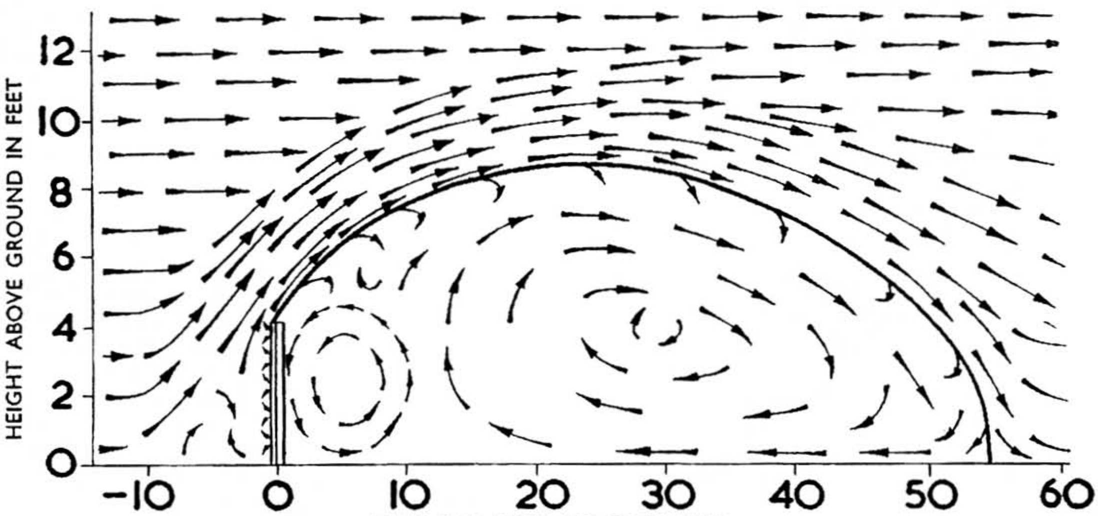

FIGURE 4b. Eddy area behind an impermeable four foot high solid fence, of 100 per cent density, (after Finney).

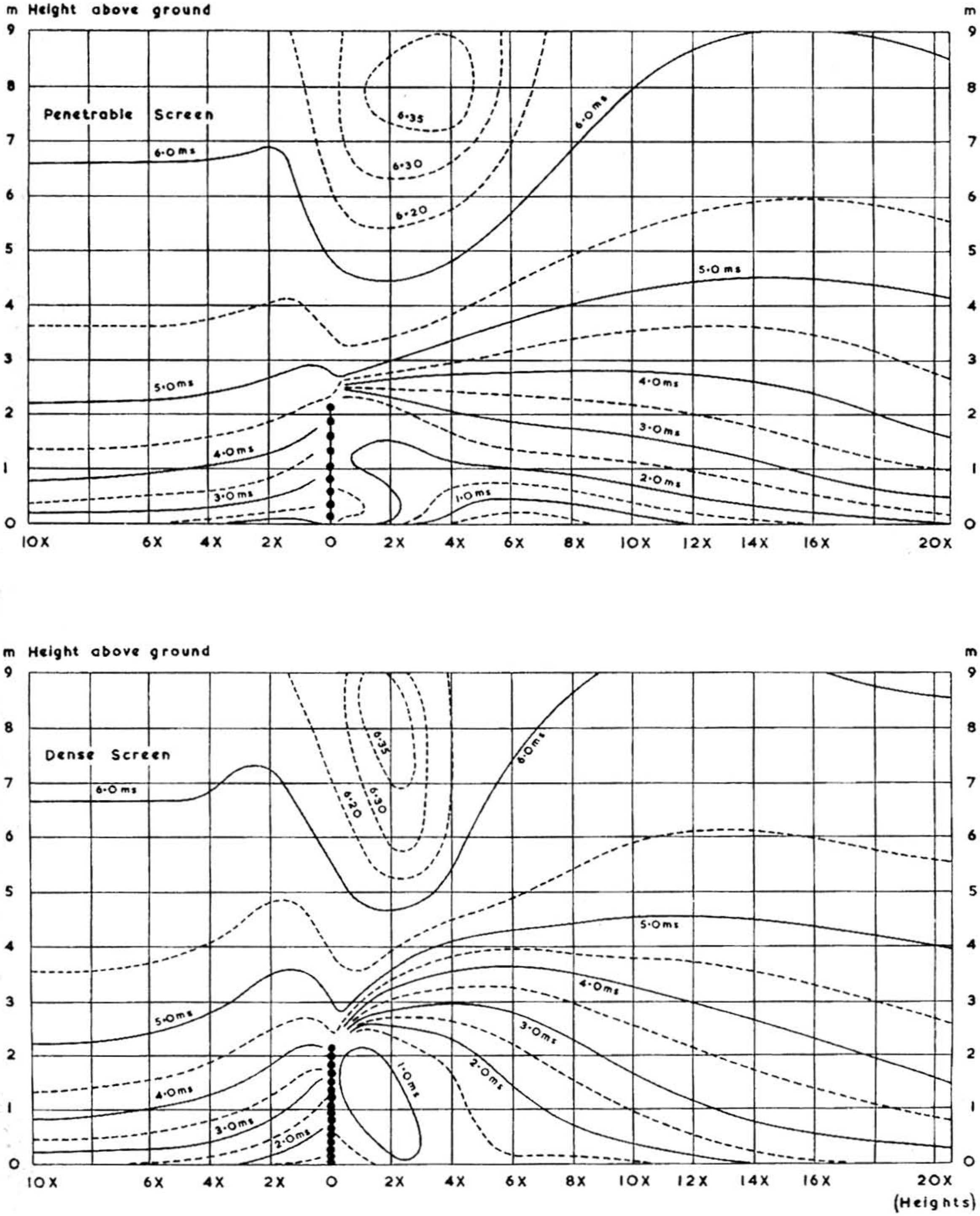

FIGURE 5. The course of lines of equal wind velocity (isotacks) in the vicinity of penetrable and dense reed screens with a free-wind velocity at 2.2m above ground of 5 m/sec. (ms = metres per second) (after Nägeli).

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,

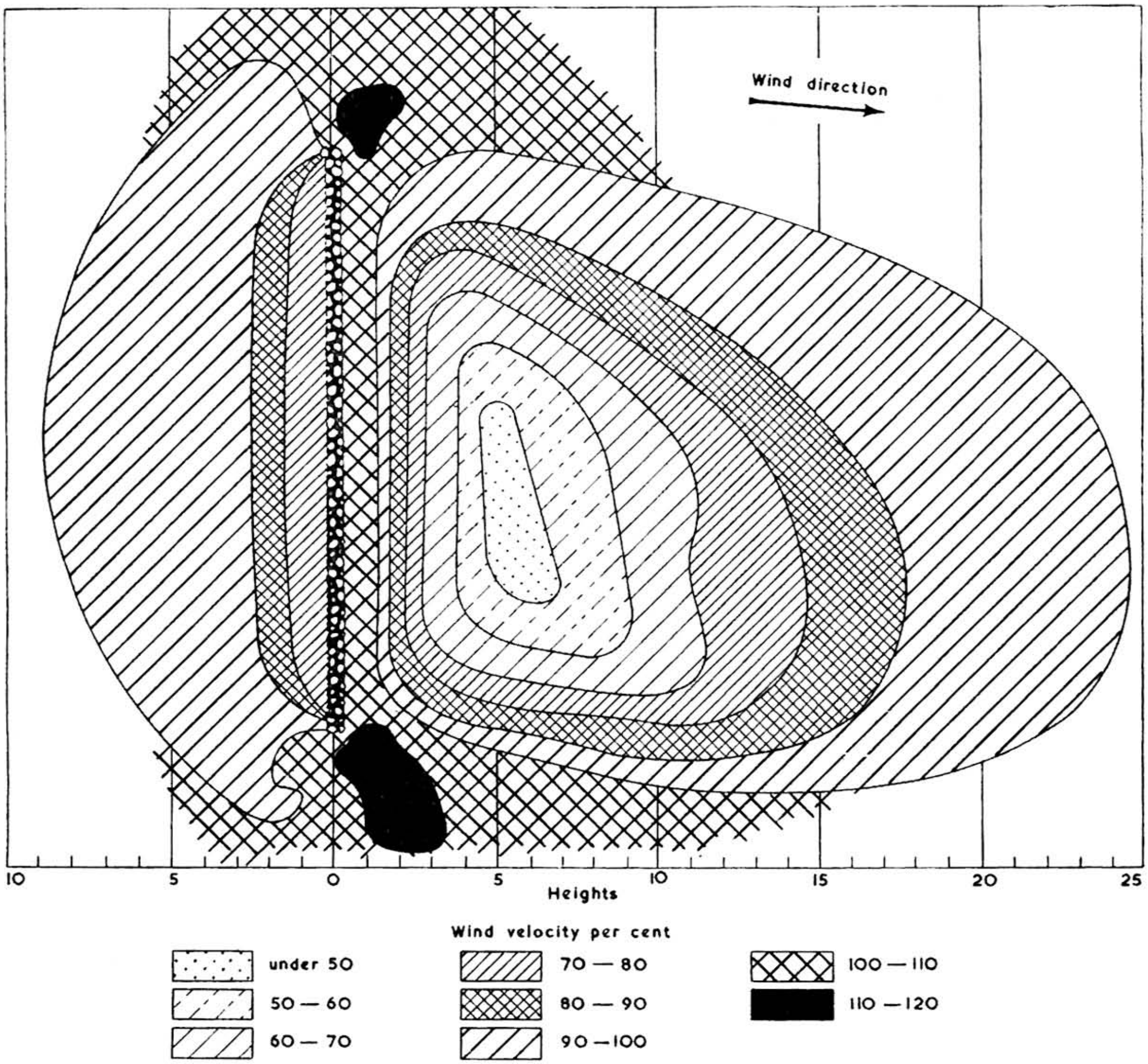

FIGURE 6. Zone of wind velocity abatement near a windbreak of moderate penetrability, (after Bates).

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

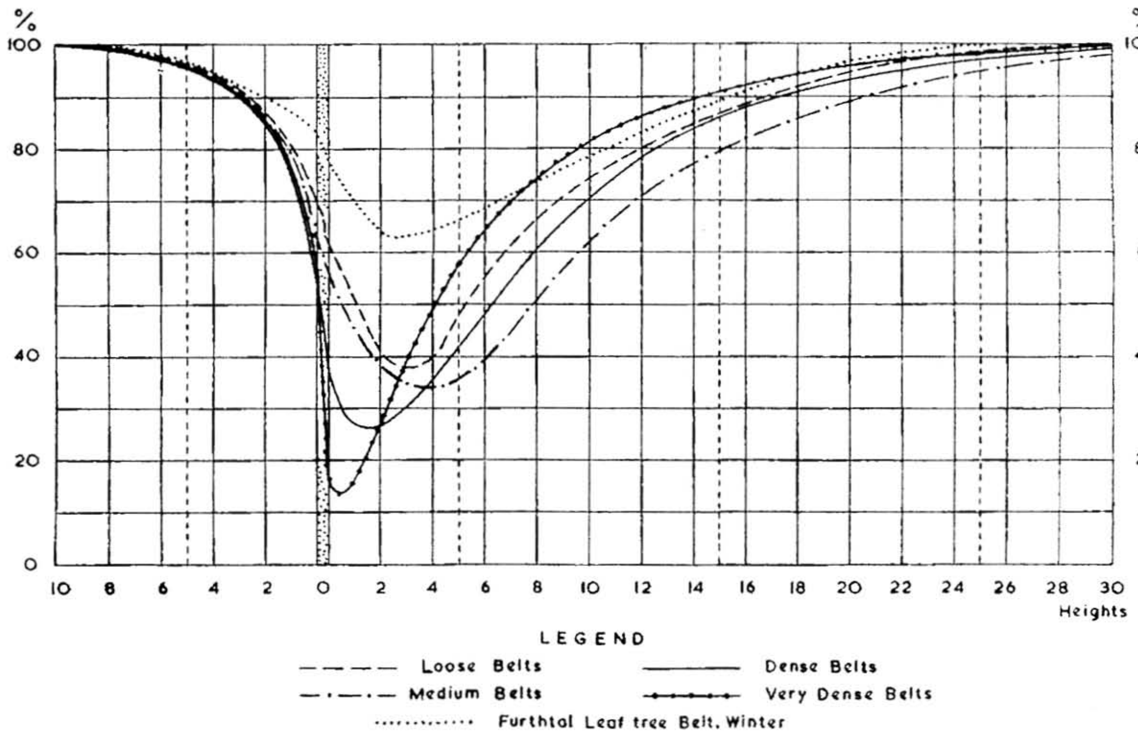

FIGURE 7. Relative wind velocities in the vicinity of Swiss shelterbelts of different degrees of penetrability, (after Nägeli).

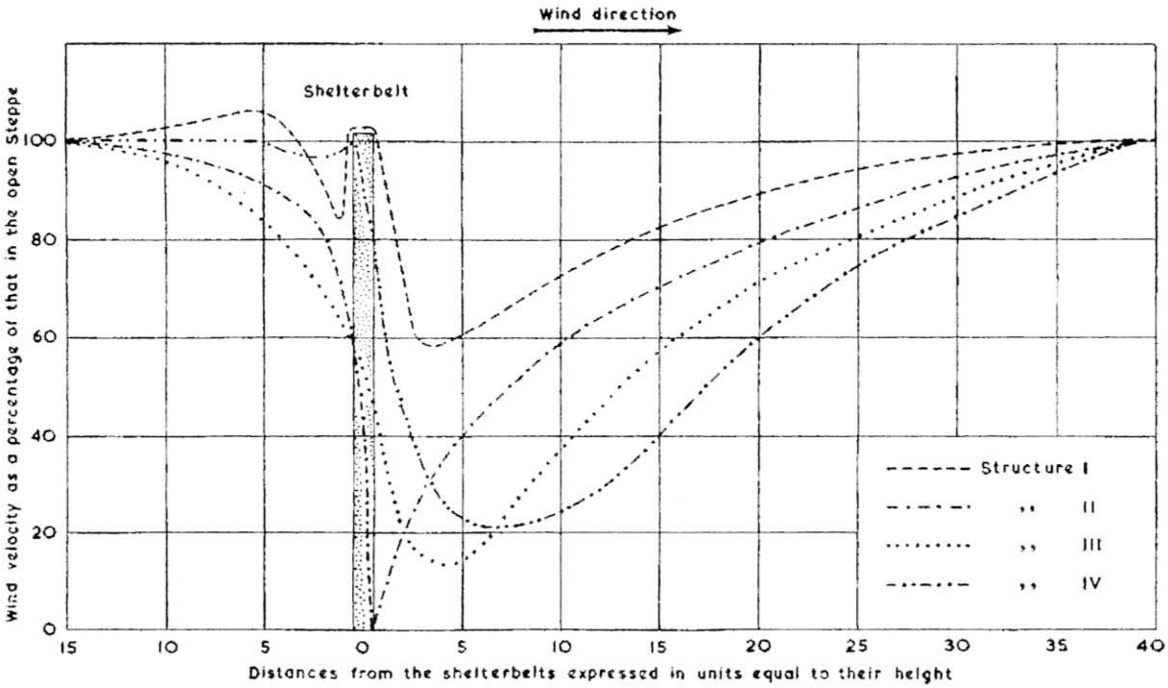

FIGURE 8. Relative wind velocities in the vicinity of Russian shelterbelts of different structure, (after Panfilov).
Structure I = shelterbelts open throughout their height (partly penetrable to wind)
Structure II = shelterbelts dense throughout their height (impenetrable to wind)
Structure III = shelterbelts 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 wind-breaks, made with model trees in the field and also in

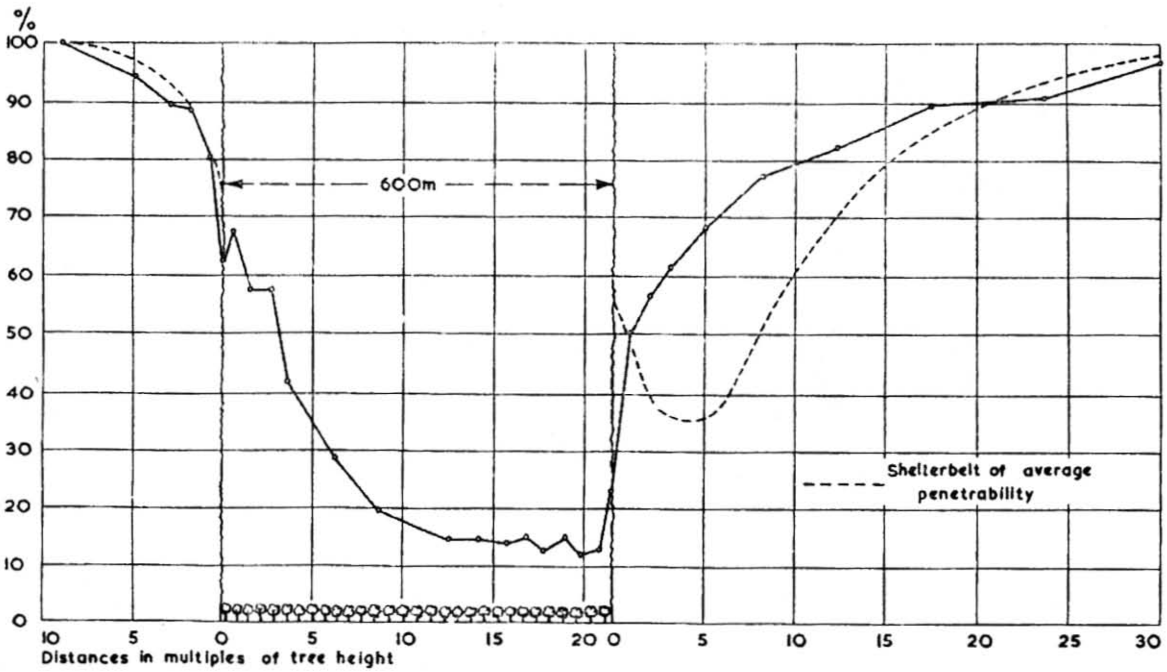

FIGURE 9. Relative wind velocities in the vicinity of a large forest complex, (after Nägeli).

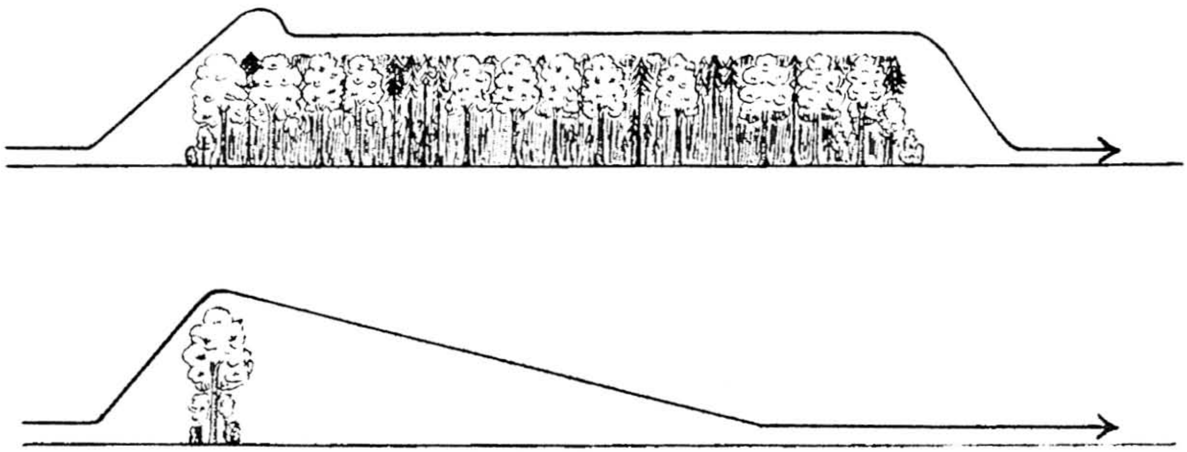

FIGURE 10. Diagram of wind flow over a forest block and a narrow shelterbelt, (after the investigations of Blenk).

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 Nokkentved (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

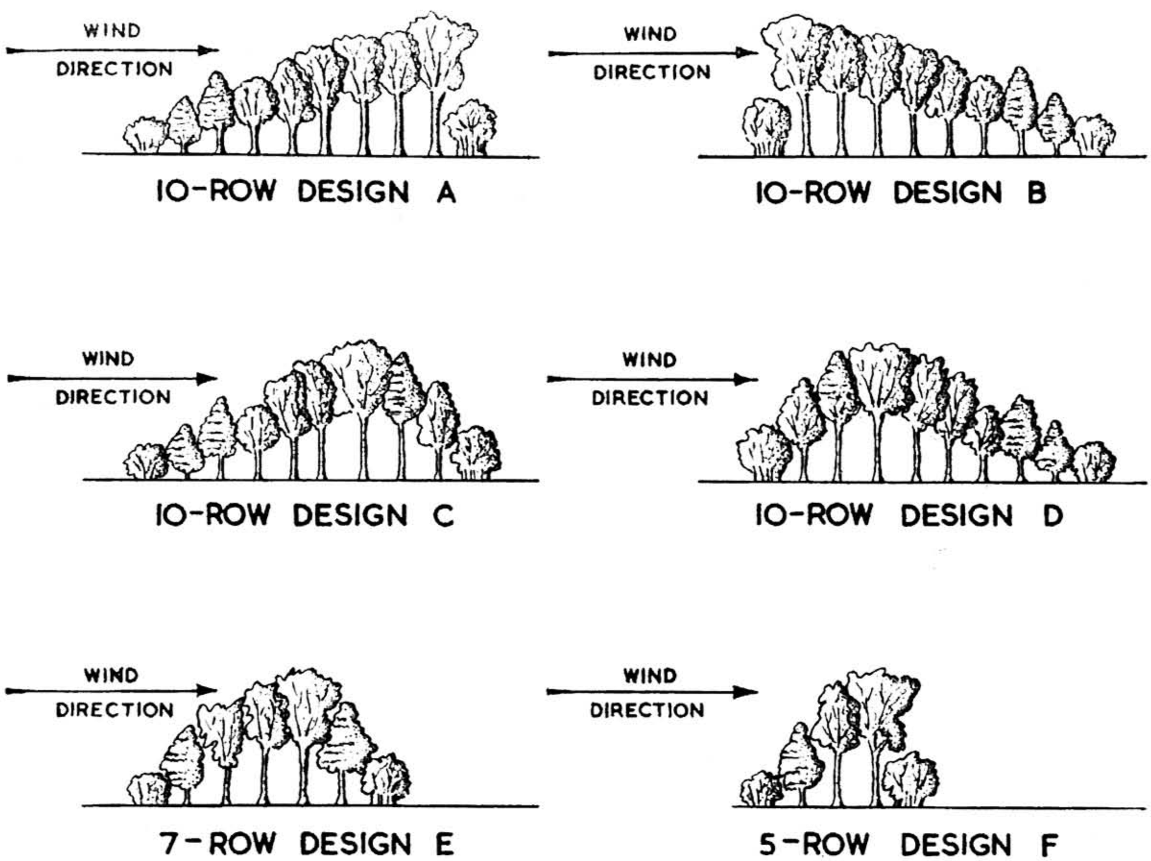

FIGURE 11. Diagram of orientation and number of tree rows in the shelterbelt models used in American wind-tunnel investigations, (after Woodruff and Zingg).

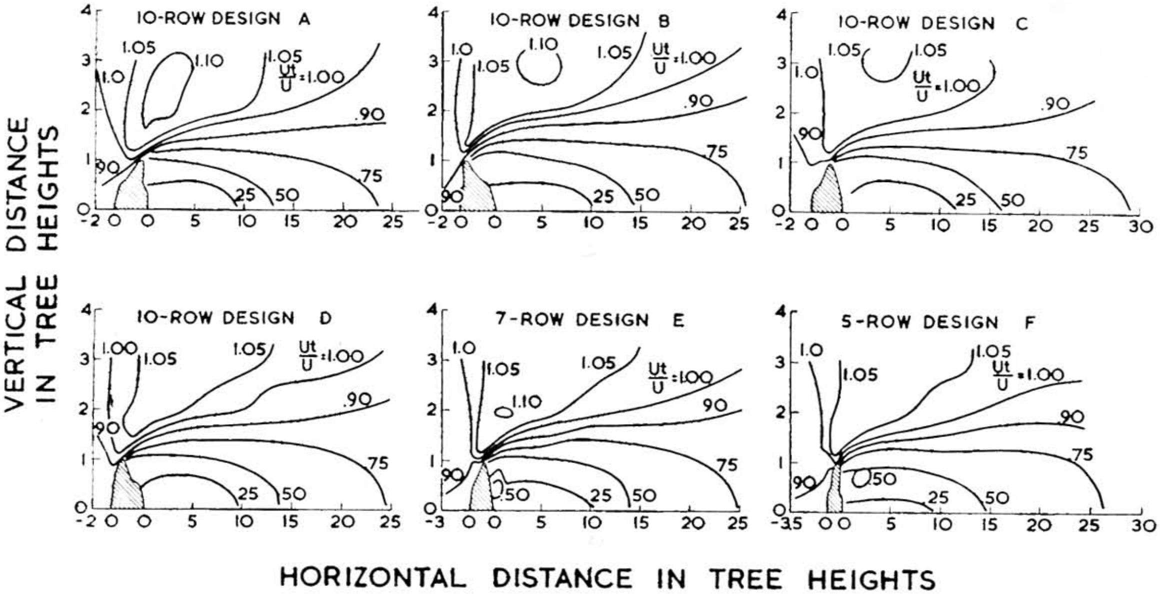

FIGURE 12. Velocity ratios U_t/U_c obtained in the vicinity of the models shown in Figure 11, (after Woodruff and Zingg).

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 $\frac{1}{4}$ 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

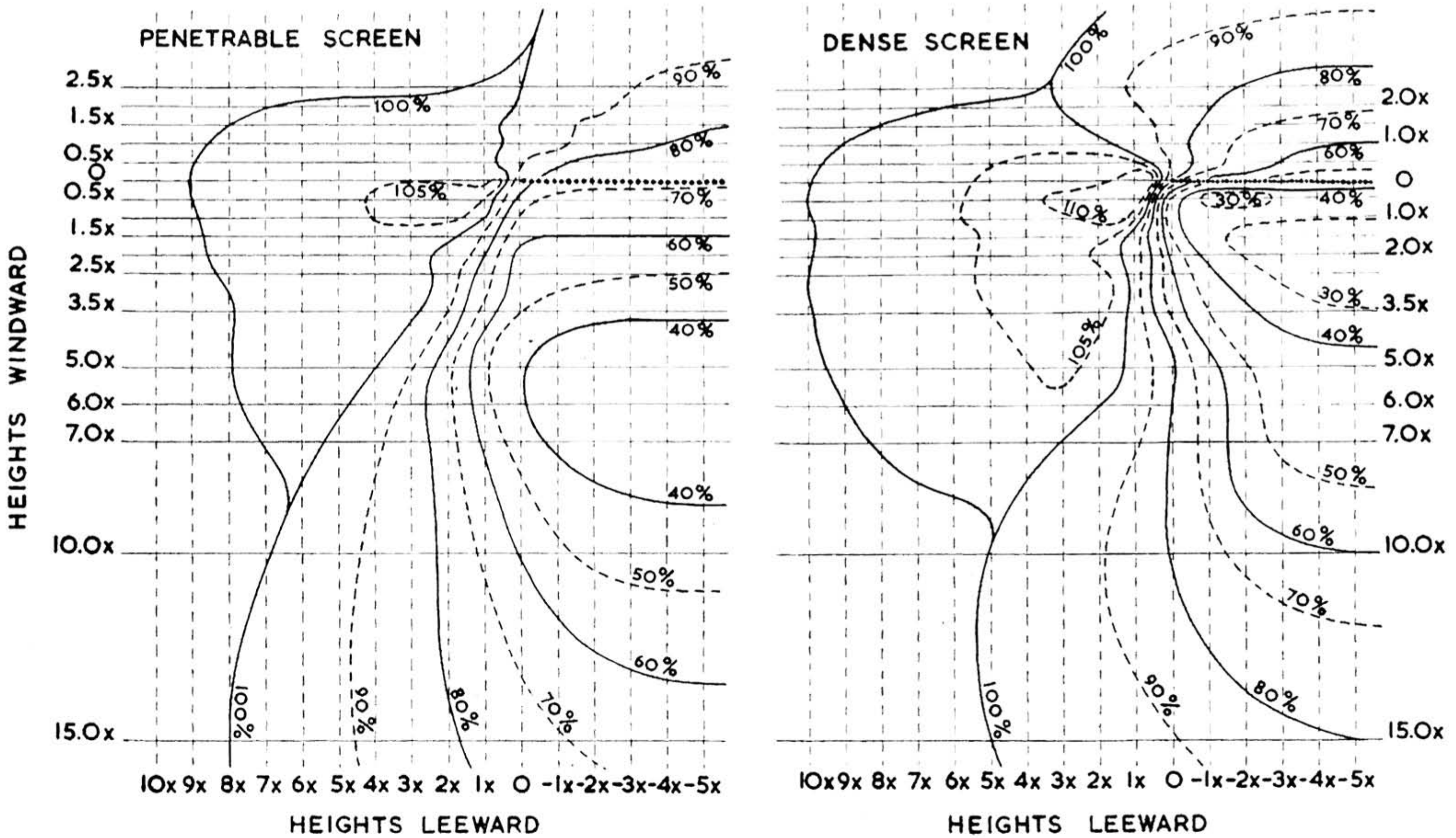

FIGURE 13. Plan of wind velocity abatement by penetrable and dense reed screens. (Height of measurement, 0.55m = ¼h), (after Nägeli).

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

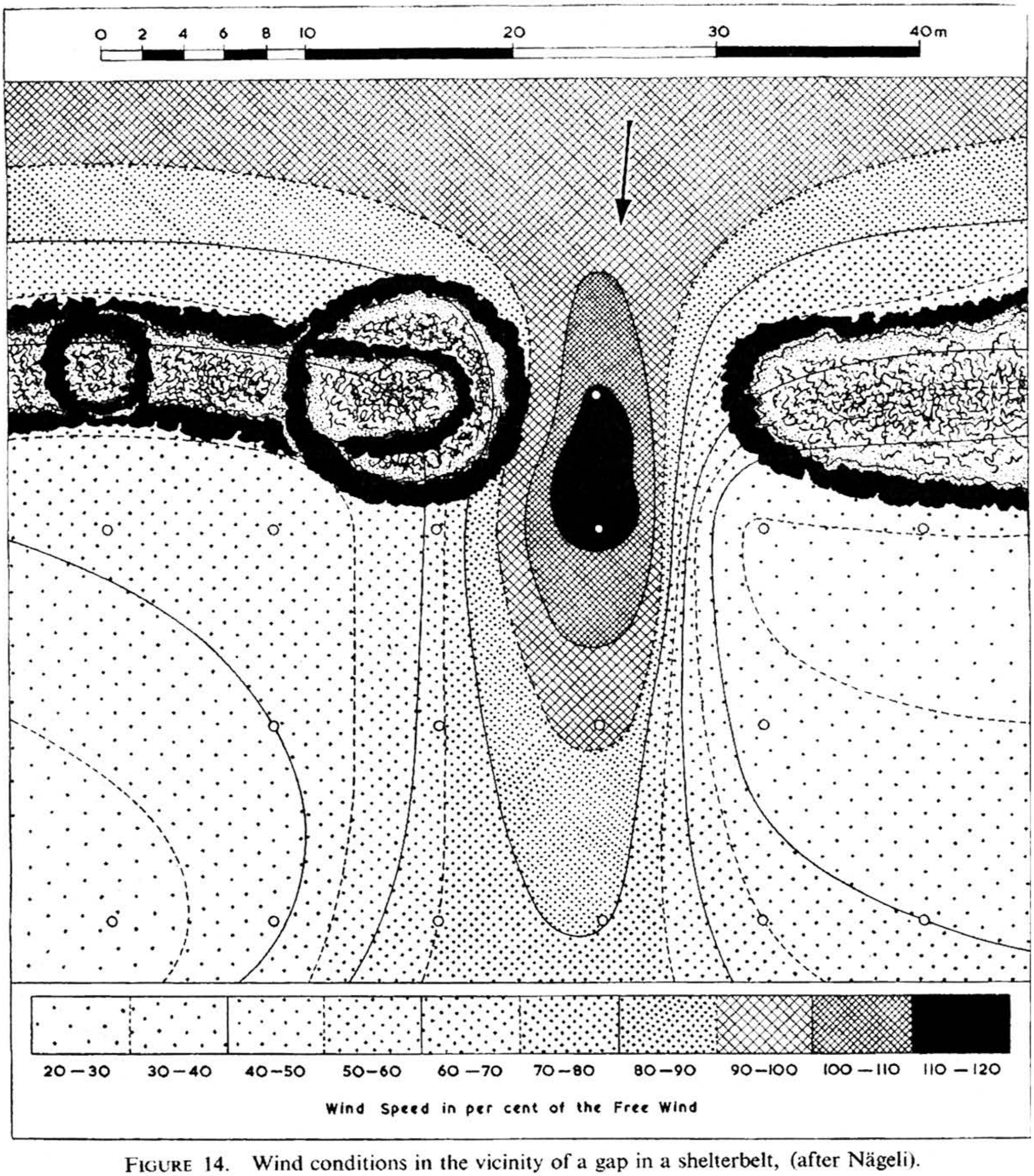

FIGURE 14. Wind conditions in the vicinity of a gap in a shelterbelt, (after Nägeli).

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.