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.

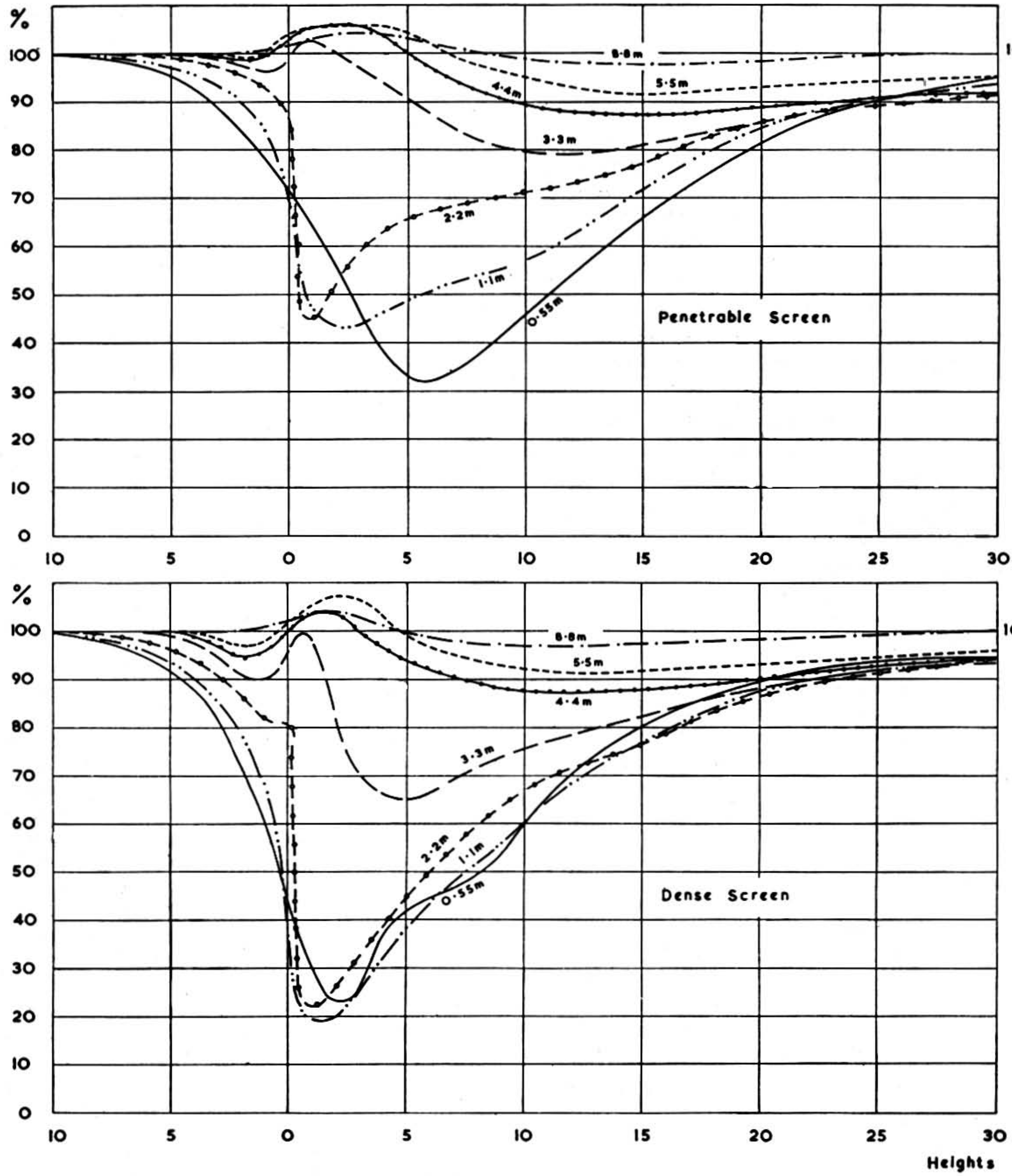

FIGURE 15. Relative wind velocities at different heights above ground in the vicinity of penetrable and dense windbreaks, 2.2m in height. (m = height in metres) (after Nägeli).

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 1½°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 3½°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		37½ m		12½ 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

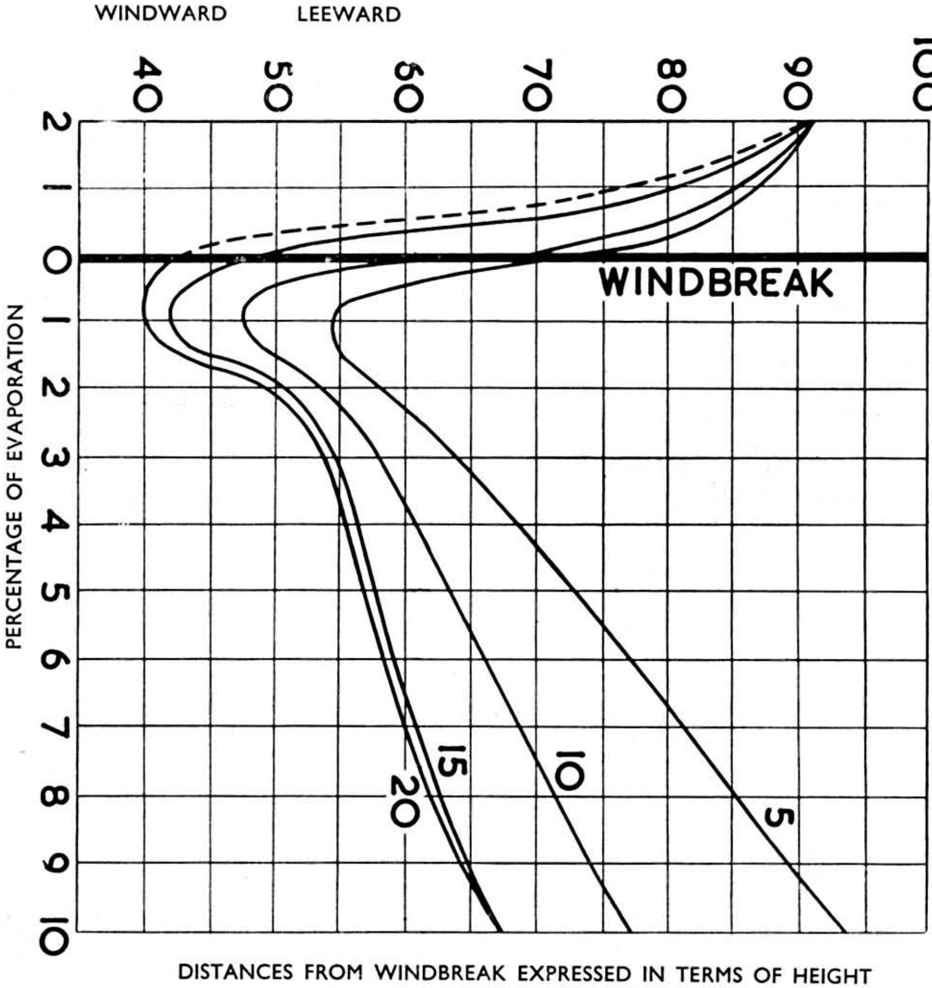

FIGURE 16. Relative evaporation rates in the vicinity of underplanted cottonwood (Poplar, *Populus* species) groves in the United States of America for various wind velocities of 5, 10, 15 and 20 mi/hr. Average height 75 ft.; 70 readings, (after Bates).

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

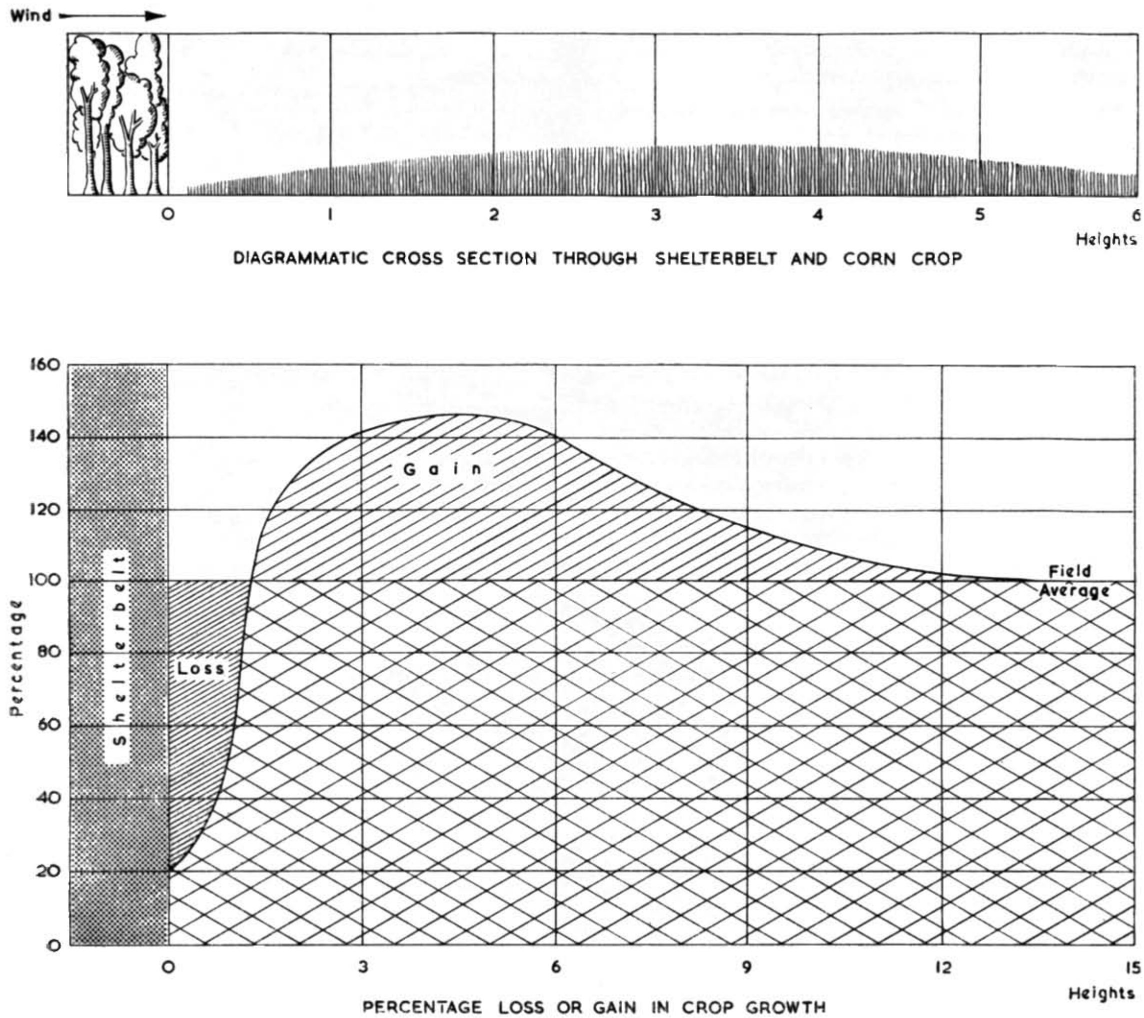

FIGURE 17. Effect of a shelterbelt on crop yields, (after Bates).

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 4½ 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 microenvironment 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 over-shading, 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 wind-firm 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 $2\frac{1}{2}$ chains, Cadman (1953) 2 or 4 chains, Guillebaud (1943) $2\frac{1}{2}$-3 chains. These widths have been suggested with the intention of a certain amount of timber production. An experimental belt of 19 rows, $1\frac{1}{2}$ 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 $7\frac{1}{2}$ 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

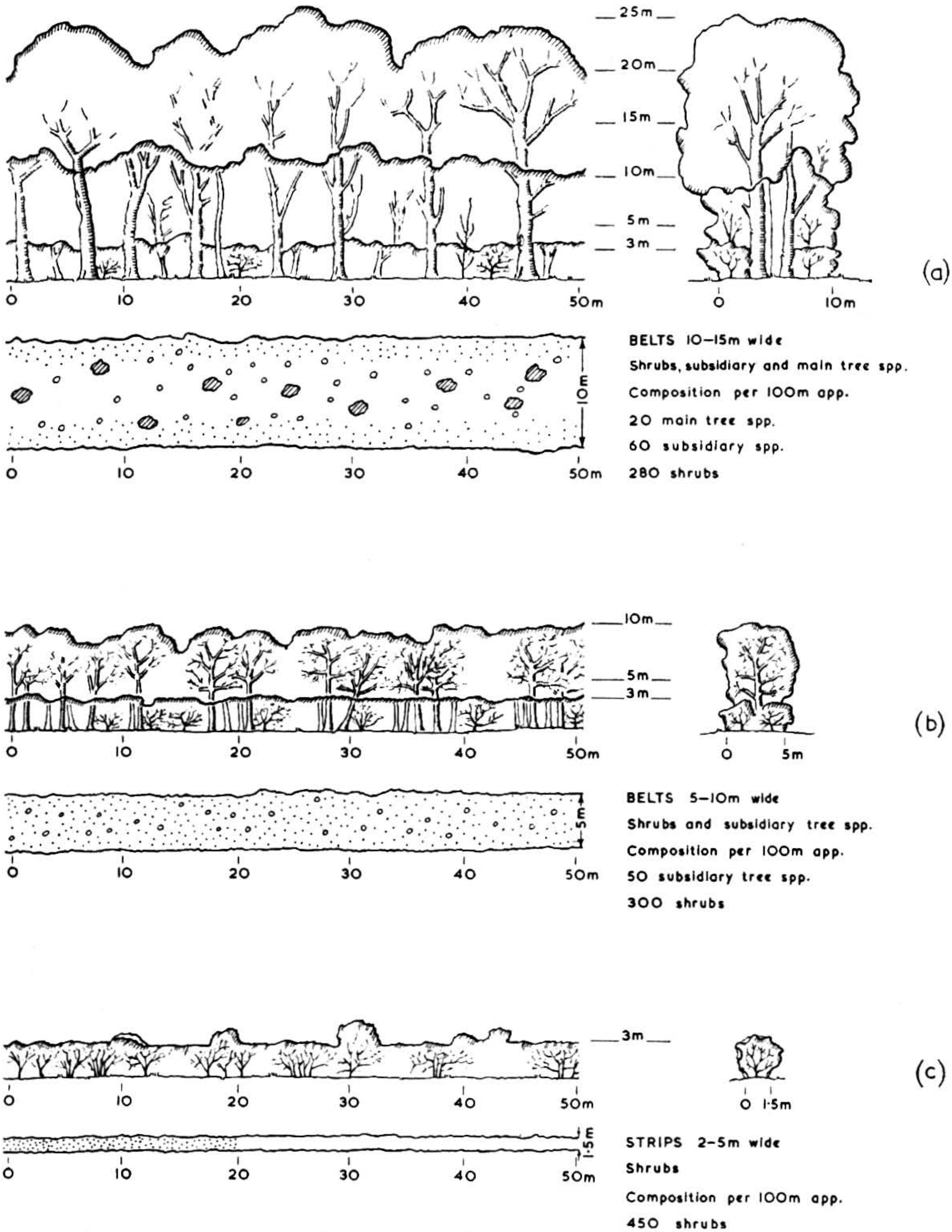

FIGURE 18. Scheme of shelterbelt types, St. Gallen Canton, Rhine Valley, Switzerland, (after Tanner & Nägeli).

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 wedge-