Shelterbelt Effects in Tropical and Temperate Zones

A. Martin Jensen

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SHELTERBELT EFFECTS IN
TROPICAL AND TEMPERATE ZONES

Summary of Findings for
African Drylands

A. Martin Jensen
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During the past 10 years, the International Development Research Centre (IDRC) has held technical meetings in Africa to permit directors of forest research institutes and heads of forestry services from various countries in dry zones to discuss policies and priorities in forest research. These meetings were the basis for several projects in applied research funded in part by IDRC grants.

In answer to the wishes expressed by several African forestry experts, IDRC has supported, since 1975, a pilot project designed to promote cooperation in forest research. An important activity of this project is the preparation of studies and seminars to collect and disseminate available expertise on specific subjects that are of great interest to many countries. Specific recommendations have been made concerning studies in the following three priority areas: reforestation in very dry zones; the effects of shelterbelts in tropical and subtropical zones; and the technical and economic aspects of irrigated forest plantations.

The first study, on reforestation techniques in subdesert regions of Africa, was published by the IDRC in 1981 (IDRC-169f). This publication, the second in the series, is the work of Martin Jensen, of Denmark. He consulted existing documents in the main forestry libraries in Europe, and went on missions to several countries bordering the Sahara desert to collect unpublished information and to observe results that had not been outlined in reports.

This study, like the previous one on reforestation techniques, is not comprehensive, because the author did not have all the time required to prepare a full report on all aspects of shelterbelts under irrigated and dry conditions. However, we believe that the information gathered and the observations made by the author are useful for resource managers, who must consider the advantages and disadvantages of shelterbelts under specific conditions.

IDRC already supports several projects in the north and the south of the Sahara to quantify the effects of the main types of shelterbelts on agricultural production and on the microclimate in various ecological zones. It is hoped that this research will extend expertise on the role of shelterbelts in agriculture in the dry zones of Africa.

L.G. Lessard,
Deputy Director,
Agriculture, Food and Nutrition Sciences Program,
International Development Research Centre
Shelterbelts are used for protection of crops against wind erosion in countries located in temperate zones.

In Denmark alone, 58,000 km of shelterbelts were planted between 1876 and 1963 (105). In the United States, between 1934 and 1942, 30,000 km were established to counter the mounting threat of wind erosion in the vast central plains and the rate of planting is now about 7,000 km/year (51). In the European sector of the Soviet Union, over 1 million km of shelterbelts have been planted since 1930 (104).

With the spread of desertification in the Sahel zone during the last decade, wind erosion being the most common cause (118), the use of shelterbelts in the rehabilitation of the affected zones is of considerable interest (13, 43, 60, 125). Opinions, however, are divided with respect to their use in dry-farming of African arid zones (40, 63). Some authors (36, 74) would restrict use of shelterbelts to the protection of irrigated areas and others to areas of dryland cultivation (63); however, Poulsen (112) suggests using trees throughout the agricultural areas as a means of combating wind erosion.

Unfortunately, only scant experimental data is available on shelterbelts in tropical zones. This deficiency was revealed by Eimern et al. (45), who, while compiling literature on shelterbelts and wind erosion, found that only 8 of 1020 documents on the subject referred to tropical zones.

The situation has not improved since then, and in fact only one study, by Fougerouze (52), has been published on the subject of biological effects of shelterbelts in tropical climates and it refers solely to the situation in the West Indies.

The important role of shelterbelts in combating desertification is also recognized in North Africa. Although several studies have been based on projects carried out under a Mediterranean climate, only one (48) describes the biological effects of shelterbelts on dryland cultivation.

To correct this situation, the International Development Research Centre (IDRC) resolved to subsidize studies on shelterbelts in four African countries (125). From a review of the literature and from data collected on a field trip, this publication summarizes the findings to date on the potential role of shelterbelts in the dry tropical zone of Africa.

The first part summarizes the experience acquired in temperate zones to facilitate interpretation of the scant data available on the effects of shelterbelts in tropical zones. The second part is an analysis of the effects of shelterbelts in tropical and Mediterranean zones. Finally, the third chapter summarizes the conclusions of the study and suggests other measures for the protection of dryland cultivation from wind erosion in the Sahel and the Sudanese zones.

The author advocates the planting of trees scattered throughout the territory, rather than shelterbelts, for African drylands. He describes this method as "screen afforestation."

Acknowledgment

This publication summarizes the findings to date on the subject of shelterbelts in African drylands. I thank all the scientists who agreed to meet me and allowed me to draw on their research findings and their experiments.
Among these collaborators who should be mentioned are: F. Olesen, horticultural engineer, Denmark; G. Guyot, chief of research, France; F.Y. Adekiya, doctor of silviculture; Y. Roederer, chief engineer, the Cameroons; E. Ekoko-Etouman, engineer, the Cameroons; H.K. Musnad, silvicultural researcher, the Sudan; Dr M. Hoshy El Lakany, chief assistant, Egypt; A. Khoudjja, state-works engineer, Tunisia; and O. Mimirit, professor of silviculture, Morocco.

My special thanks go to M.G. Poulsen of IDRC, my research adviser and traveling companion; to J.M. Fleury of IDRC, to whom fell the tedious task of revising the manuscript; H.J. Jensen, horticultural engineer; to my wife who prepared the figures that illustrate the text; and particularly to Dr M. Jensen, for his valuable comments at the conception of this publication.

To all those who contributed to this work, I express my sincere gratitude.
Chapter 1

SHELTERBELTS IN TEMperate ZONES

Very few experimental results confirm the usefulness of shelterbelts in African arid and semi-arid regions. In fact, the establishment of protective barriers in these regions is based on the assumption that they will have the same beneficial effect as in temperate zones (15, 35, 128, 129, 130, 145). This assumption is no doubt tenable with respect to physical effects, but is certainly less valid when it comes to biological factors. For example, would it be reasonable to expect that a shelterbelt would increase the yield of a millet field in the heart of the Sahel in the same manner that it improves the wheat harvest on the Ukrainian steppes?

In the description of the effect of shelterbelts in temperate zones therefore, four physical parameters - wind velocity, air temperature, evapotranspiration, and erosion - are stressed. Temperate-zone biological effects are considered in depth only insofar as they apply to crops in tropical arid zones.

1. Effect on Wind Velocity

Shelterbelts modify evapotranspiration and affect wind erosion by decreasing wind velocity. The study of their aerodynamics is therefore of prime importance. Moreover, shelterbelts have the same effect on airflow in varying conditions, described later, independent of the climatic zone.

Figures 1 and 2 show the effect of shelterbelts on airflow. For example, on the windward side of an impermeable (airtight) shelterbelt at a distance of five times the height (5 H), wind velocity at mid-height (0.5 H) drops to about 80% of the control velocity, which is defined as the wind velocity at the same height in an open area. At a distance of 14 H on the leeward side, however, wind velocity at 0.5 H is 82% of the control velocity and drops to 73% if the shelterbelt is permeable.

Jensen (68, 69, 70) has described the aerodynamic effects of shelterbelts on the basis of wind-tunnel tests on models 5 cm high that were subsequently amplified by measurements on 2.5-m palisades constructed in an open area. He then compared these results with data obtained in natural conditions for areas exposed to the wind, and for areas sheltered by windbreaks of trees.

1 "Leeward" wind velocity is the velocity downwind from the shelterbelt; "windward" wind velocity is the upwind velocity. Measurements are taken at the same height and in the same time interval.

2 Distances to a shelterbelt are expressed as fractions or multiples of its height: H.
Fig. 1: Series of wind isovelocity curves for the vicinity of an impermeable, 2-m high shelterbelt. The control velocity is measured at the level of the upper edge of the shelterbelt, where it is unaffected by its interference (65).

Fig. 2: Series of wind isovelocity curves for the vicinity of a permeable, 2-m high shelterbelt. The control velocity is measured at the level of the upper edge of the shelterbelt, where it is unaffected by its interference (65).

Definitions

Aerodynamic characteristics are of interest because of their uniform effects, wind flow being modified by a shelterbelt to the same extent, irrespective of wind velocity. Thus, a value referred to as efficiency, which can be measured at every leeward point of the shelterbelt, is defined as follows:
Efficiency = 1 - (leeward wind velocity/windward wind velocity)

In agriculture, the most important factor is the efficiency near the soil surface where the crop is grown. Wind-tunnel tests have shown that, irrespective of air turbulence, efficiency is a constant for heights above ground level equal to or less than 0.4 H. Needless to say, efficiency is greatest closest to the shelterbelt and decreases with distance.

Furthermore, given that efficiency can be considered a constant below 0.4 H, the overall shelter curve is drawn with efficiency measured at a height equal to or less than 0.4 H as the ordinate, and the distance leeward from the shelterbelt, measured in multiples of its height, as the abscissa. Figure 3 shows the overall shelter of two shelterbelts with permeabilities of 36% and 72%.

The overall shelter can then be reduced to a single figure by integration of the surface under the curve. Thus, for a shelterbelt with a 36% permeability, a shelter index of 13 is obtained; with 72% permeability, the shelter index is 7. For obvious reasons, these calculations do not consider efficiencies of less than 10%.

In practice, the aim is to reduce velocity below a given threshold and thus protect crops from wind erosion and prevent windfall of fruit in orchards. For this reason, it is important to establish the overall shelter curve that indicates the area of the protected zone.

![Wind direction chart](image)

**Fig. 3:** Overall shelter curves measured upwind and downwind of shelterbelts with permeabilities of 36% and 72%.

**Nature of the Wind**

Guyot (65) has reviewed the literature and summarized his own findings on the effect of wind turbulence on the protection afforded by shelterbelts.

All the studies confirm that both the efficiency and the extent of the protected area decline with increased turbulence of the air mass. It is noteworthy that the degree of turbulence can be due to a number of factors: atmospheric instability, topography, ruggedness of the surface (a field of wheat has a coarser texture than a lawn), and the shelterbelts themselves.
It follows that efficiency values obtained in one region cannot be directly applied to another.

**Positioning of a Shelterbelt**

Obviously the most efficient positioning is a 90° angle to the wind direction.

As long as the incidence of the wind to be shelterbelt exceeds 45°, the overall shelter is adequate (71). However, the area of shelter will also depend on the permeability of the shelterbelt, which decreases as the wind direction changes from a 90° angle. Thus, a shelterbelt with numerous gaps can become impermeable if the wind blows at an oblique angle.

Generally speaking, and provided too great a loss in shelter is not entailed, some deviations from the optimum positioning are acceptable, for example, when the shelterbelt network must be adapted to a system of roads and irrigation canals.

**Height**

The area protected is a linear function of the height of the shelterbelt (Fig. 3). In optimum conditions, it extends as far as 20 H downwind from the shelterbelt. Its direct relation to height means that protection increases with time. Thus two shelterbelts are often established at half the optimum distance, so that one of them may be replanted at mid-rotation and the system kept at its prime. Unfortunately, the planner's objective is often forgotten in practice. Overly dense shelterbelts are often seen in several older sections in North Africa, such as Mitidia in Algeria, Béni Khaled in Tunisia, and Tharir in Egypt.

**Length**

If the wind direction is at 90°, the area downwind from the shelterbelt is protected uniformly, provided the length of the shelterbelt exceeds 12 H (97). On the other hand, if the direction of prevailing winds varies within a 90° range, as it does in Denmark, then maximum protection exists at the middle of the shelterbelts, provided that length is increased to 50 H (106). Sometimes openings must be made in shelterbelts for roads or irrigation canals. Wind velocity increases in such gaps, but shelter is soon reestablished if the height of the opening is greater than its width.

**Thickness**

On the basis of work by Caborn (29), the effect of shelterbelts of variable thickness on wind velocity is difficult to determine, as their permeability is not constant. However, his results confirm the theoretical values and the results of Jensen (69) that show that when thickness is greater than 1 H but less than 20 H overall shelter is reduced.

In terms of cross-sectional profile, rectangular protective fringes are preferred, although wind-tunnel tests show no particular disadvantages for shapes leaning into the wind, provided the angle is 45° or more (29). It would even seem that, for very high winds, this type of profile is more efficient for very dense shelterbelts (138).
Penmeability

The efficiency of a shelterbelt decreases when the proportion of gaps is 36-72% (Fig. 3) and increases when it is 0-30% (Figs. 1 and 2). Research has shown that optimum permeability is achieved when the proportion of gaps is about 40% (65).

Figure 1 shows the form of the sheltered area in the lee of impermeable shelterbelts. For a distance of up to 4-6 H, a large vortex of wind is formed with velocities almost equaling those in the open, but blowing in the opposite direction. Efficiency is reduced proportionally. Behind an impermeable shelterbelt, the same air mass is, in effect, in circulation. Horizontal air movement is thus considerably reduced. Turbulence created by an impermeable shelterbelt (Fig. 2) disappears rapidly when permeability reaches 25% (65).

It would be dangerous to use measurements obtained with artificial screens as the sole criterion for determining optimum permeability and spacing between shelterbelts. Very little information on the silvicultural measures that would result in optimum permeability can be found in the literature. With barriers made up of one or two rows of conifers, would not thinnings result in an unsuitable configuration? Should optimum permeability be tested by pruning? No answers to these questions have been found.

The problem is further complicated by the fact that, in natural shelterbelts, permeability varies with height. Shelterbelts with the lower part of the trunks bare offer less overall shelter (68, 103); yet it is sometimes claimed that some permeability of the lower part improves the performance of compact shelterbelts (64). Shelterbelts that are impermeable at the base produce a marked, though reduced, turbulence for a distance of 2 H (64).

Lastly, permeability of natural windbreaks varies with wind velocity; with increased velocity, it increases in the case of broadleaved species and decreases with most conifers (65).

Shelterbelt Systems

Unexpectedly (Fig. 4), the effect of a secondary shelterbelt is less pronounced than that of the first (29, 68, 101). The reason might be that the first windbreak increases air turbulence and results in less efficient shelter behind the second windbreak.

It follows that, on a scale of several kilometres, the shelter effect of a shelterbelt system is not cumulative. Experimental results obtained with a single shelterbelt cannot, therefore, be extrapolated to a whole system.

Forest Shelter

Both theory and wind-tunnel measurements (68) show that shelter efficiency in the lee of a forest with a width of 20 H is considerably less than that of a single shelterbelt. Efficiency improves when the width of the forest is greater than 20 H. In Fig. 5, efficiency in the lee of a forest with a width 100 H is compared with that of a system of three shelterbelts: the shelter index for the system is 50% greater than that of the forest. If, therefore, the objective is to protect agricultural and grazing lands from the wind, the inferior performance of wide forest belts should be noted.
Fig. 4: Wind isovelocity curves for the vicinity of two small-scale models of shelterbelts (SB1 and SB2) spaced at 15 H in a wind tunnel (65).

Fig. 5: The upper efficiency profile applies to the lee of a 50-m wide forest with trees 5 m high. The lower profile applies to the lee of three shelterbelts each 5 m high and 100 m apart. The shelter index of the shelterbelt system is 50% higher than that of the forest (68).

Regional Shelter

The isovelocity curve 1.0 in Fig. 4 rises in the lee of the first shelterbelt and continues to rise slightly in the vicinity of the second shelterbelt. It would rise even higher if there were a third shelterbelt. However, the 0.4 isovelocity curve falls in the lee of the first shelterbelt, rises in the vicinity of the second, then falls again in its lee. There are, therefore, two types of shelter: one that is derived from individual obstacles and is close to the ground surface; this type, as already observed, is not cumulative. The other type is located at the top of the shelterbelts and derived from the distortion created by the shelterbelts. This type depends on the distance covered by the
cannot be discerned from one shelterbelt to another. Clearly, the gradual formation above
the shelterbelt of a wind layer of a reduced velocity influences shelter near the surface.

There are two measures for regional shelter effect due to uneveness of a terrain
where shelterbelts have been established: Jensen (68) defines regional efficiency as:

\[ \text{regional efficiency} = 1 - \frac{V_r}{V_0} \]

where \( V_r \) is the wind velocity measured outside the influence of individual shelterbelts
and \( V_0 \) is that measured in an area without shelterbelts.

In southwest Denmark, Jensen has found regional efficiencies increasing by 20, 30,
and 40% for respective distances of 10, 20, and 40 km covered by the wind, whereas Guyot
and Séguin (67) have found a regional efficiency of 30-50% in the farmlands of Brittany
crisscrossed by hedges and trees.

If regional efficiency figures are compared with those of overall shelter curves
for the lee of individual shelterbelts (Fig. 3), it can be concluded that, for
considerable areas, regional shelter is as important as that provided by shelterbelts
taken individually.

2. Effect on Temperature

The shelterbelts modify the thermal conditions of the air close to the soil in a
way that depends greatly on the water status of both soil and vegetation. Thus, results
of trials in temperate areas cannot be transferred directly to tropical and subtropical
areas.

Temperatures Near the Surface

Figure 6 shows thermal gradients near the surface over a 24-hour period. This
data is from a desert zone with very broad daily thermal fluctuations.

![Figure 6: Temperature variations from ground level to 1 m above ground surface for 25 April 1950; taken at the Beni Abbés oasis (110).](image-url)
At midday (12 hours), the ground surface is heated to 55°C (measurements are taken at a 5-mm depth to prevent direct radiation on the thermometer). At 10 cm above the ground, air temperature reaches 38°C and at 1 m it is 32°C. When the wind is blowing, air masses at the 1-m level mix with the hotter air near the surface and cool the ground. In general, the wind velocity reduction increases daytime temperatures near the surface. The increase, obviously, depends on the efficiency of the shelter.

With impermeable shelterbelts, air temperature is also increased, even though wind velocity is not much reduced in the lee of the shelterbelt, because essentially the same air mass circulates behind the shelterbelt. This is confirmed by the measurements shown in Fig. 7.

![Diagram showing raised and lowered temperatures in the shelterbelt system](image)

**Fig. 7:** Warming and cooling of air in the lee of an 8-m high shelterbelt (impermeable for the first 5 m). Measurements were taken at midday. Wind temperature and velocity, taken at 2 m above the surface in the open, were 35°C and 6.8 m/sec respectively (140).

During the night, the reverse process occurs and warm winds warm the surface cooled by radiation. By slowing air circulation, shelterbelts contribute to the lowering of night temperatures near the surface.

If warm winds also blow during the day, for example a "foehn" (very pure, warm and dry air currents, as in Alpine areas), then the nighttime process prevails even during the day (100). Warm winds are relatively rare in temperate zones and, for the reason, most studies show a rise in day temperatures and a drop in night temperatures under the influence of a shelterbelt.

**Radiation Balance**

A diagram of solar radiation in a shelterbelt system (Fig. 8) demarcates one shady zone and one exposed to the sun. In the latter, radiation is increased by the shelterbelt, which acts as a mirror for the sun, and uneven heating of the soil results. For the overall system, however, the amount of radiation remains the same, the gain in the exposed area being balanced by the loss in the shaded area.
Shelterbelts significantly modify the albedo (reflective coefficient). In actual fact, the sky is visible in the angle between two shelterbelts and, the higher and closer the shelterbelts, the more acute is the angle. Thus, part of the radiation is received by the system. Guyot and Séguin (67) have shown that the albedo increases from 16% to 20% as the distance between shelterbelts is increased from 4 H to 32 H. Shelterbelts, therefore, reduce the quantity of reflected radiation. It follows that the majority of studies in temperate zones show that, in protected zones, decreases in night temperatures are amply compensated by increases in day temperatures. Bouchet (26) estimates that in Brittany in France, these changes in the energy balance are equivalent to a move of 100-200 km southward. Olsen (105) points out that such a change results in spectacular yield increases of crops cultivated near their northerly limit.

Fig. 8: The effect of a shelterbelt system on solar radiation.

**Moisture Content of the Soil and of Plants**

Solar energy received on the surface is used in several ways. A very small portion, 4% at most, is used in photosynthesis. Another portion contributes to the evaporation of water from the ground and to plant transpiration and warms the ground and the air. Finally, a certain proportion is reflected; the amount varies according to the nature of the surface albedo. A desert for example reflects 50% of the solar energy received whereas a coniferous forest reflects only 10% (14).

Because photosynthesis absorbs only a very small fraction of radiation and because albedo is more or less constant for a given plant cover, the part used for warming the ground and the air remains fairly constant. Thus, air is warmed to a lesser degree as evapotranspiration increases as has been confirmed by Aase and Siddoway (1). They measured temperature drops of 2.2°C at midday in an area protected from the wind. Shelterbelts had conserved ground moisture that had evaporated in the open area.

3. Effect on Evapotranspiration

The effect of shelterbelts on evapotranspiration (ET) is manifested in two ways, which are usually contradictory. Shelterbelts both reduce water vapour exchange by slowing movement of air around the leaves, and promote vapour exchange by reducing the relative humidity of the air by raising the temperature. However, plant transpiration is not only a physical but also a biological process. To understand better the effect of shelterbelts on actual evapotranspiration (AET), the water transportation mechanism in the soil-plant system should be reviewed briefly.

Evaporation on the surface of the ground depends simply on the degree of humidity. In the case of a moist soil, it approaches potential evapotranspiration (PET), whereas in a dry soil it depends on the rate of diffusion of water vapor in the soil. A drop in wind velocity above a dry surface has little effect on evapotranspiration because air movement of 2-3 m/sec is quite sufficient to mix and dilute the scant volume of water vapor released (81).
Transpiration, on the other hand, is controlled by the stomata of plants. In the morning, as stomata are exposed to light, chlorophyll begins to produce sugars and osmotic pressure rises. If water is available, the stomata absorb it, swell, and open. If water transpired by stomata exceeds the quantity available, the stomata close. Several factors come into operation.

Transpiration and water supply may be out of phase because the air is very dry or wind velocity is high. Also, roots may no longer be able to meet demand, or the plant's vascular system may be incapable of supplying water even when it is available in sufficient quantity in the soil. Equally, water in the soil may be lacking.

When stomata are closed, water vapor is released to the atmosphere solely through the cuticle, and if cuticular transpiration exceeds available water supply, the plant begins to wilt. Cuticular transpiration is always lower than stomatal transpiration, for the same saturation deficit of the air and the same wind velocity. In terms of plant production, the important factor is the daytime period of transpiration of the stomata.

![Graph showing transpiration and water supply](image)

**Fig. 9:** The effect of modifications in potential evapotranspiration and in water supply on actual evapotranspiration (INRA model, France): A - Open zone (PET greater than q); B - Sheltered zone (PET less than q); and C - Open zone (q is reduced because of water shortage in the soil).
Researchers from the Institut National de Recherche Agricole (INRA) in France have analysed the influence of various alterations in the microclimate and moisture conditions and on agricultural yields (25, 27, 62, 107). Figure 9A shows the conditions in an open zone. Stomata open at sunrise and AET follows potential PET until water supply to the leaves is no longer satisfactory, i.e., when PET approaches maximum water supply to the leaves at point q. At this point, the stomata partially close and PET falls below AET. The process is reversed at the end of the day.

In a sheltered zone (Fig. 9B), PET is lower because of reduced wind velocity, and remains less than q during the whole day and thus equals AET, both being lower than PET in a nonsheltered zone. This represents the effect of shelterbelts on PET and AET in temperate zones.

When water in the soil is used up and q becomes smaller (Fig. 9C), the stomata begin to close in the morning. At midday, they are completely closed and the plant subsists only by cuticular transpiration, which is normally less than q.

If shelterbelts reduce PET to the level of q, as indicated in Fig. 9C, AET is increased because its reduction at midday has been canceled out. Normally, because PET is lowered, AET would be expected to rise, but here, paradoxical as it may seem, AET has risen in spite of a drop in PET. The validity of this model has been confirmed by measurements made in the United States (122, 124) and in Australia (137).

It is difficult to foresee the effect of shelterbelts on AET, in view of the complexity of the previously described processes. Rosenberg (123) has shown simulation results from a mathematical model based on empirical data from shelterbelt experiments. With all the other factors constant, a wind velocity reduction from 0.5 m/sec to 0.25 m/sec would lower AET by only 6%. On the other hand, an increase in air temperature from 23°C to 26°C would increase AET by 16%. The impact of temperature on evapotranspiration has been confirmed by Aslyng (6), who found that PET was lowered in a sheltered area by 10% during a hot summer (mean temperature of 14.9°C), but by 20% during a cool summer (mean temperature of 12.6°C). These findings might be valid for moderate variations in climate observed in temperate zones. However, because it is difficult enough to establish whether shelterbelts conserve water or not, it is still more difficult to forecast what their effect would be on evapotranspiration in different climates.

4. Effect on Wind Erosion

Planting of shelterbelts is most frequently justified by the possibility of wind erosion. The direct effect of shelterbelts on wind erosion has, however, been the subject of very few experimental studies. The bulk of our knowledge consists of deductions from studies of the mechanisms of wind erosion and also of the effect of shelterbelts on wind velocity.

Bagnold (8) has studied sand movement in wind tunnels and in the field from a geomorphological point of view. Chepil and Woodruff (34) have taken a basically agro-pedological approach to wind erosion phenomena. They have summarized their own work and that of others on mechanisms of soil ablation and on combating wind erosion. The following description is based to a large extent on their publications, which are all the more interesting because the findings in temperate zones are fully applicable to other climatic zones, wind erosion being a strictly physical phenomenon.
If soil particles are projected into the air, their velocity, because of air friction, becomes constant. The equilibrium velocities for various texture fractions are shown in Table 1.

Table 1. Free-fall velocities by grain size distribution (8).

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<th>Fraction</th>
<th>Diameter (μm)</th>
<th>Equilibrium velocity (m/sec)</th>
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<tbody>
<tr>
<td>Coarse sand</td>
<td>0.2-2.0</td>
<td>1.0-15</td>
</tr>
<tr>
<td>Fine sand</td>
<td>0.02-0.2</td>
<td>0.3-1.0</td>
</tr>
<tr>
<td>Silt</td>
<td>0.002-0.02</td>
<td>0.003-0.3</td>
</tr>
<tr>
<td>Clay</td>
<td>&lt; 0.002</td>
<td>&lt; 0.003</td>
</tr>
</tbody>
</table>

Considerable turbulence is thus needed to move sand in the air. However, silt and clay once airborne remain so as long as there is the slightest air movement.

The textural composition of the soil is sifted in this manner by wind erosion. The fine components are carried in the form of dust clouds over considerable distances, whereas the coarse material remains on the site, either in the form of sand dunes or of an impoverished surface horizon.

Wind applies two forces to a grain of sand on the surface: a force of propulsion derived from the fact that wind velocity is almost nil at the surface, while at the level of the upper part of the grain it already has a certain value; and lift resulting from the wind velocity gradient, whereby, according to Bernoulli's law, pressure is reduced on the upper part of the grain.

As gravity is partially canceled, the grain begins to rotate on the surface of the ground and the wind velocity on its upper part increases, while the rotating motion at the base has a braking affect. The grain of sand is thus projected in the air. This process is known as the Magnus effect.

With increased height, wind velocity decreases, air friction slows rotation and cancels the Magnus effect. At this point, the grain begins its descent on a trajectory determined by wind velocity and gravity. When the grain comes in contact with the ground, it resumes its rotating motion and is once again projected into the air by its impact with other grains of sand on the surface. This impact also displaces sand grains on the surface, either by rolling them along the surface - a displacement called reptation - or by making them bounce - called saltation.

Once saltation has started, the grain of sand tends to remain in this state because the wind velocity required to maintain saltation is less than that needed to initiate it. The minimum wind velocity required to initiate saltation is called the saltation threshold and that required to maintain it is called the impact threshold, the latter being 80% of the former (79).

It is implicit in the mechanics of saltation, that one grain of sand in this state propagates it to others. The cumulative effect, called the avalanche effect, results in wind erosion intensity being a function of the distance involved.

The saltation threshold varies with the size of the sand grains. Obviously, a size is reached where the particles can no longer be moved by wind because of their weight. The upper limit for saltation is, in fact, 0.55 mm diameter (33). On the other
hand, the propelling force and the Magnus effect require a minimum grain diameter and thus there is a lower limit below which the wind, regardless of its velocity, is no longer able to lift the particles. This lower limit is 0.02 mm (33). Particles most subject to wind erosion are therefore about 0.1 mm in diameter.

The literature gives no clear information on the precise thresholds of saltation. In some instances, wind velocity is measured at various heights, in others, extrapolation from the 2-m height is unreliable because the texture is not specified. Nevertheless, Chepil and Woodruff (33) as well as Olesen (105) agree that the saltation threshold, for agricultural soils subject to wind erosion, is at a wind velocity of 8 m/sec, measured 2 m above ground level. The saltation threshold is lower for dune sand. According to Bagnold (8), it is about 5 m/sec, although Khulman (79) places it between 5 and 7 m/sec.

The volume of sand moved in saltation and reptation increases with the cube of the difference between wind velocity (V) and the saltation threshold (Vt), i.e., (V - Vt)^3 (8). Two measures can, therefore, be applied to reduce wind erosion: wind velocity can be modified and the saltation threshold can be altered by structural improvement of the soil. The latter measure is of limited value for very sandy soils. Moreover, it is observable that exceptional winds are the main cause of erosion.

If the foundation on which saltation takes place is not dry sand but a consolidated surface, a clay soil between dunes or a petrochemical mulch for example, the transport velocity is three times greater than on dry sand (80).

For the avalanche effect to occur, both the distances required for maximum erosion and the maximum distances between artificial barriers required to reduce wind erosion to an acceptable level, changes with soil particle size (Table 2).

Table 2. Wind erosion due to the avalanche effect (31) in a 13-m/sec wind and a 8-m/sec saltation threshold, at a height of 2 m.

<table>
<thead>
<tr>
<th>Texture</th>
<th>Distance required for maximum erosion (m)</th>
<th>Distances between 30-cm barriers to control erosiona (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>33</td>
<td>6</td>
</tr>
<tr>
<td>Silty sand</td>
<td>53</td>
<td>8</td>
</tr>
<tr>
<td>Sandy silt</td>
<td>280</td>
<td>30</td>
</tr>
<tr>
<td>Silt</td>
<td>700</td>
<td>75</td>
</tr>
<tr>
<td>Silty clay</td>
<td>1000</td>
<td>105</td>
</tr>
</tbody>
</table>

a) Maximum wind erosion acceptable at the downwind end of the field is 50 kg of soil per hour on a 1-m front.

Sandy soils are by far the most vulnerable to erosion and a high density of barriers is required to check dune erosion effectively. However, the barriers need not be appreciably higher than 30 cm because it has been established that 90% of particles in saltation jump less than 30 cm from the surface in dry sand.

Fine-textured soils are less subject to wind erosion. Nevertheless, if affected by the abrasive action of sand grains in saltation, they will also erode.
Soil structure, in the form of clods, increases resistance to wind erosion. Not only are the clods too big to be carried by the wind, but they also shelter soil particles subject to wind erosion. In this case also, however, the abrasive action of sand grains leads to destruction of the clods. Moisture increases the cohesion of soil particles and therefore reduces erosion.

In summary, shelterbelts exercise a twofold control over wind erosion. They both trap moving sand and reduce wind velocity, thus preventing the saltation threshold from being reached. To trap sand, it is necessary for the shelterbelt to reduce wind velocity to below the impact threshold. If, for example, wind velocity is 13 m/sec and the saltation threshold is 8 m/sec, then the impact threshold is $8 \times 0.8 = 6.5$ m/sec. A shelterbelt would have to be very permeable for its efficiency to be less than 50% immediately behind its screen. Sand is, therefore, almost invariably halted at the shelterbelt itself or directly behind it.

If a shelterbelt controls the downwind area so that the saltation threshold is never attained before the wind reaches another shelterbelt, then the system will fully control wind erosion.

The extension of the area in the lee of a shelterbelt where the saltation threshold is not exceeded is calculated directly from the shelter curves (see Fig. 3). If the saltation threshold is not be exceeded, wind velocity decrease must be greater than $1 - (8/13) = 38\%$. With optimum permeability, this decrease applies to an area less than 14 H. This value agrees with the work of Chepil and Woodruff (33), which shows that, for protection against wind erosion, the optimum spacing between shelterbelts is about 10 H.

It should be stressed that in combating wind erosion, it is particularly important to eliminate saltation because it is this phenomenon that causes reptation and the movement of particles in suspension. Once the saltation threshold has been passed, 30-50 m are sufficient for the avalance effect to reach its peak on sandy soil. For this reason, low hedges at short intervals are a more efficient means of combating wind erosion than high, widely spaced shelterbelts.

5. Effect on Agricultural Production

Shelterbelts influence agricultural production in several ways. They lessen damage by the mechanical action of wind and modify the thermal and moisture environment of plants.

In the first instance, wind velocity must be reduced below certain thresholds at specific stages of the crop cycle. In the case of cereals, for example, it is important to control wind erosion from seeding until the crop itself is sufficiently developed to control the problem. In tree-fruit culture, toward the end of the season, untimely gusts of wind may cause serious fruit windfall.

These shelterbelt effects, although the most important, are seldom studied because their random nature makes them unsuitable for experimentation. Nevertheless, it is to prevent this type of damage that crops are protected in certain regions.

Experiments in temperate zones have shown that the establishment of shelterbelts is generally a paying proposition, even though they take a certain area out of agricultural production.

Cereal Crops

The greatest increase of cereal production has been reported in the Soviet Union. The average increase was 25% in a zone 20 times the height of the shelterbelt and the best
results were obtained in years with low precipitation. For the Great Plains of the USA, Rosenberg (124) is more conservative and concludes that production increased slightly or remained the same. Numerous tests in Denmark show an average increase in production of 5% in a zone 20 times the height of the sheltering trees (105).

In a test near Paris, in the course of which both the shelter and the water supply were appropriately managed, significant differences were obtained between open and protected zones (Table 3).

Table 3. Shelterbelt effect on wheat yield with or without irrigation (27).

<table>
<thead>
<tr>
<th></th>
<th>Open zone</th>
<th>Protected zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield (kg/ha)</td>
<td>6830</td>
<td>7870</td>
</tr>
<tr>
<td>Water balance (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precipitation</td>
<td>93</td>
<td>93</td>
</tr>
<tr>
<td>Irrigation</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Soil depletion</td>
<td>320</td>
<td>280</td>
</tr>
<tr>
<td>Total water used</td>
<td>413</td>
<td>373</td>
</tr>
<tr>
<td>Water efficiency</td>
<td>1.65</td>
<td>2.11</td>
</tr>
</tbody>
</table>

aYield at a grain moisture content of 15%.

bWater efficiency is calculated by dividing the grain yield (kg) by the volume of water consumed (m^3).

To appreciate the significance of the differences between open and sheltered zones shown in Table 3, it would be useful to review the physiological effect of shelterbelts that is shown in Fig. 9.

Cereal production depends on the length of the diurnal period during which plant stomata are open. The work of Parcevaux (107) and an examination of Fig. 9 seem to indicate that there is a link in the AET/PET ratio and assimilation. If AET equals PET, that is if AET/PET = 1, transpiration is by means of open stomata. If, on the other hand, AET/PET is less than one, stomata are more or less closed and net assimilation approaches zero. Thus, in the tests shown in Table 3, water is used more efficiently where shelterbelts reduce PET and increase AET and where the water deficit is reduced in irrigated soil. Other tests, in the course of which both PET and AET were subject to variation, have confirmed these results (122, 124, 137).

In cereal crop production, only one part of the yield counts: the kernels. An increase in the yield of total dry matter without an increased kernel yield can be disappointing. Thus, Guyot (63) refers to an experiment with corn in the Rhone Valley where leaf and stem yield increased 138%, but kernel yield was not improved.

Forage Crops

In Denmark, shelterbelts always increase yields of hay, clover, and alfalfa (105), specifically in the above-ground portion of the plants. A single exception, reported by Guyot (63), shows that, in hot and arid conditions, shelterbelts have a detrimental effect on yield. In a very hot and dry summer near Toulouse, France, yield in the second alfalfa crop was reduced 20%.
Crop development is also affected by shelterbelts because they increase spring temperatures. Early fruit and vegetables are the items that show the most spectacular economic rewards. Olesen reports a case where revenue increased 60% at the first harvest and 15% at the second. In other cases, he reported revenue increases of 100%. In Denmark, fruit harvests in the vicinity of shelterbelts have increased by over 30%, the effect being limited, however, to a distance of 20 H (105). Yield increases of up to 160% for pears have been reported in Holland, but the increase of fruit production was not accompanied by increased vegetative development. It would seem, therefore, that in this specific case, shelter at blossoming was the reason for obtaining such spectacular results.

These examples emphasize the danger of extrapolating the biological effect of shelterbelts from one area to another.

Livestock

Very little information on the influence of shelterbelts on livestock production can be found in the literature. In Denmark, Kirsgaard and Andersen (76) have studied shelterbelt effects on milk production and the weight gains of cows between April and October in 1968-1970 (Table 4). During this experiment, herds in both zones received the same quantity of additional fodder.

<table>
<thead>
<tr>
<th>Product and year</th>
<th>Zone</th>
<th>Ratio of sheltered: open</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Open</td>
<td>Sheltered</td>
</tr>
<tr>
<td>4% milk (kg/day)</td>
<td>15.6</td>
<td>15.4</td>
</tr>
<tr>
<td></td>
<td>16.3</td>
<td>17.1</td>
</tr>
<tr>
<td></td>
<td>18.1</td>
<td>18.5</td>
</tr>
<tr>
<td>Butter (g/day)</td>
<td>611</td>
<td>618</td>
</tr>
<tr>
<td></td>
<td>636</td>
<td>678</td>
</tr>
<tr>
<td></td>
<td>717</td>
<td>740</td>
</tr>
</tbody>
</table>

*In 1968, the summer was humid, but in 1969 and 1970 they were dry.*

The results in Table 4 can be interpreted as follows: during dry summers, hay production is significantly higher in the sheltered zones than in the open zones and the surplus of fodder results in increased milk production. However, in each of the 3 years, herds in the open area gained up to 9% more weight. Heifer fattening showed the same results (105). Ignoring fodder production, this Danish experiment has shown that shelterbelts have a negative effect or no effect at all on meat production. Bond (24) has even found that wind has a slight, positive effect on the weight gain of cattle. No difference has been reported for pigs. Many farmers believe that shelterbelts are beneficial to animal husbandry. They mention increased forage production, but especially that the shelter effect during cold spells would tend to reduce the mortality rate of the more vulnerable young animals.
Chapter II

SHELTERBELTS IN TROPICAL AND MEDITERRANEAN ZONES

Only one study in depth, that by Fougerouze (52), discusses the effect of shelterbelts in tropical zones. Somewhat more extensive literature is available for the Mediterranean zone. It would, however, be too restrictive to consider only the experiments of scientists. If shelterbelts are a part of traditional agriculture, it is surely because their protective role was recognized.

Shelterbelts associated with traditional agriculture are to be found along the Mediterranean and Atlantic coasts of North Africa, where market-garden crops are often protected by nonliving shelterbelts constructed from reeds of Arundo donax the so-called "Provence cane".

Less systematically, but still traditionally planted, are Populus nigra shelterbelts, associated with the irrigated agriculture of the high plateaus of North Africa: Aures and Oued Touil in Algeria, and along the foothills of the Middle Atlas bordering on the upper basin of the Moulouya in Morocco. Their purpose, of course, is to produce lumber, but it is unlikely that they would have been kept up if they did not also provide shelter for the crops. Similarly, Bhimaya (19) has found traditional shelterbelts of Populus and even Tamarix species on the high plateaus of Iran, even though Tamarix does not produce lumber.

South of the Sahara, there are no traditional shelterbelts of trees. Nevertheless, in the Sahel and in the Sahel-Sudan zone, low aligned hedges are to be found, especially in the regions of intense wind erosion. Andropogon gayanus, for example, is found in the region of Kano and of Maradi, hedges of Euphorbia balsamifera in the Sudan, and Euphorbia tirucalli in Upper Volta (87, 111).

Why do African farmers south of the Sahara not use shelterbelts of trees to control wind erosion?

In fact, they combat erosion with large scattered trees, which are often maintained in fields for several reasons. The fact that plantations of Acacia albida in the Kano and the Niger regions were protected by ancient laws that prohibited cutting proves recognition of their utility. In Rajasthan in India, Prosopis cineraria is the object of religious cults and, although farmers know how to grow it (57), it is found growing at random in the fields rather than in shelterbelts. To state that shelterbelts are not beneficial south of the Sahara, or generally in dry tropical climates with a short rainy season, would perhaps be a mistaken conclusion. It may, at least, be concluded that the advantages of scattered trees outweigh their disadvantages.

Today, many shelterbelts in the traditional style have been established in Africa. Shelterbelts of single or double rows of Cupressus sempervirens and Casuarina spp. are invariably associated with citrus-fruit cultivation in North Africa. Shelterbelts of Casuarina glauca and Casuarina cunninghamiana, also of sparse density, protect the large irrigated crop areas of northern Egypt. In the centre of arid and semi-arid Tunisia, shelterbelts of Eucalyptus salmonophloia surround the rain-fed crops and the steppe-like expanses (143).

In Senegal, Anacardium occidentale has been planted on 5000 ha as shelterbelts for the control of wind erosion (50). In the Kano region, 25-m wide shelterbelts with Azadirachta indica as the main species are being planted at the rate of 10 km/year. In the northern Cameroons, 300 km of shelterbelts of variable widths were established in the late 1950s. They were composed mainly of Cassia siamea (61). In Madagascar, shelterbelts
are to be found in Androy, usually with five rows of Eucalyptus rostrata as the main species, and of these, 263 km were established in 1956-71 (47). In the Gezira basin in the Sudan, there are only 20 km of shelterbelts (15), Eucalyptus microtheca being the main species. Further north, in the Nile Province, 200 km of Prosopis chilensis shelterbelts are being established, intended to protect irrigated areas from sand. Finally, in Dongolo, not far from the Egyptian border but right in the Sahara, a project principally with Eucalyptus canadulensis shelterbelts to attempt to protect irrigated crops is now underway (94).

Almost all shelterbelts south of the Sahara are established in drylands to halt wind erosion and in the hope that they will also have a beneficial effect on crops. Irrigated areas are usually managed without shelterbelts, apparently the only exceptions being a small area in Donsé in Upper Volta and the Tondibia area in Nigeria (41, 42).

The section that follows attempts to summarize present knowledge of shelterbelts in African drylands. It is based on a review of current information and draws on field experience. Given the scarcity of experimental data on Africa, and especially on the southern part of the Sahara, a major part of the conclusions are based on extrapolation of results obtained in temperate zones.

1. Effect on Wind Velocity

Theoretically, results of research on the aerodynamics of shelterbelts conducted in temperate zones should be valid in other climatic conditions because they pertain to the laws of physics. Nonetheless, in practice, this is not the case. Indeed, Guyot (64) has written that: "The extent of the area protected by a permeable shelterbelt, which can be 20 times the height in a northern climate, will only be 12 to 14 times the height in a tropical or Mediterranean climate".

Unfortunately, very few studies are available on the zones covered in this book. Nevertheless, it has been possible to obtain some data from certain publications.

In the Mediterranean Climate

According to Guyot (65), permeable plastic shelterbelts near Avignon have a shelter index 50% lower than that obtained in the Paris region. However, Ramani (117) has found that for fairly compact Cupressus sempervirens shelterbelts near Oran in Algeria, wind velocity reduction was no longer apparent beyond a distance of 10 H. As in temperate zones, Ramani did not find that a shelterbelt system provided cumulative effects. Baldy and El Amami (9) found that, in the vicinity of Tunis, a two-row, permeable, 13-m high shelterbelt of Eucalyptus canadulensis afforded protection greater than 20% only in a leeward zone of 10 H.

Charfi (32), in a study of the aerodynamics of shelterbelts in Tunisia, has shown that overall shelter to flat and open areas corresponds to that measured in temperate zones. Shelterbelts that were bare in the lower part had low efficiency, whereas those that were formed of two rows of eucalypts filled in at the base by acacias gave the best shelter. Study of regional shelter has shown that, as in temperate zones, shelter in the lee of the first shelterbelt is greater than that behind the following belts, but that beyond a given distance, 60 H, regional shelter became apparent.

Karshon (72) reported that, on the Israeli coast in the lee of shelterbelts of Pennisetum purpureum 4 m high, the sheltered zones were at least 15 H when the wind blew from the sea, and perhaps slightly lower when the wind blew from the mountains of the interior. On the same coast, but 800 m inland and in the lee of a one-row shelterbelt of
Eucalyptus camaldulensis 8 m high, Lomas and Gat (86), measured efficiency consistent with findings in Denmark for permeable shelterbelts (69).

In other experiments, Seginer (126) found, at 30 km from the Israeli coast, that efficiency at a distance of 7.5 H in the lee of an artificial barrier of 50% permeability was reduced by one-third in markedly unstable atmospheric conditions, as compared to efficiency in stable conditions. In normal atmospheric conditions, efficiency at 20 H remained higher than 20%.

On the Persian Gulf, in Iranian Khouzistan, overall shelter curves established by Nakhdjevani (97) for screens 3 m high and with permeabilities of 0 to 50% were almost identical to those established by Guyot in the Paris region. A zone of efficiency greater than 20% extended to 14 H for compact shelterbelts, and to 20 H for the permeable type. Efficiencies were 20% lower than those measured by Jensen (69) in Denmark.

In Tropical Climates

The effect of shelterbelts in the trade-wind climate of the West Indies has been studied by Fougereouze (52). A zone with an efficiency of over 20% extended to only 11 H during the day for shelterbelts with a 50% permeability. These findings resemble the curves for turbulent and only slightly turbulent winds (Fig. 10) obtained by Guyot (63). During the night, however, the shelter curve was similar to only slightly turbulent winds. Moreover, the curve resembles that developed by Jensen (69) in Denmark.

Guyot (66) has reported efficiency indices measured in the vicinity of a compact Eucalyptus camaldulensis shelterbelt in Dongola in the Sudan. Average efficiencies for May and December 1977 (Fig. 10) show that this shelterbelt is less effective than those in temperate zones.

Summary

To achieve overall shelter, it is of vital importance to know whether shelterbelts should be spaced at 10 or 20 H. The several studies carried out on this subject in tropical and Mediterranean zones do not agree in the answer but, in interpreting the data sets, it is essential to consider their comparability. As early as 1954, Jensen (69) noted a considerable range of efficiency downwind from natural shelterbelts of the same permeability. Because it is difficult to compare the efficiency of natural shelterbelts in the literature, where permeability is seldom shown, the question is considered only on the basis of studies made with artificial shelterbelts.

These studies show that the efficiency of shelterbelts of uniform permeability depends on wind turbulence and airflow. Although it is true that efficiency also depends on the gap profile (66), it is difficult to include this factor formally in the evaluation before its importance is confirmed by more measurements.

Efficiency-reducing turbulence is created either by mechanical obstruction or by atmospheric instability. Mechanical obstruction is the reason, for example, that wind becomes more turbulent above a wheat field than above fallow land, or, even more so, above a forest or a city. Topography also plays an important role in the generation of turbulence.

Atmospheric instability, on the other hand, results from air being heated at ground level. As the temperature rises, air expands and the density of the lower layers of the atmosphere becomes less than that of the higher layers. Ascending air currents then begin to generate turbulence and, from then on, pressure at ground level decreases and wind velocity at the surface increases.

In a normal atmosphere, a shelterbelt's loss of efficiency when air movement is
turbulent occurs because the wind already has a turbulence that approaches that generated by roughness of the ground surface with a shelterbelt present. The loss of efficiency attributable to atmospheric instability is caused by turbulence created by ascending currents, and also by the diminished friction of air masses because of reduced pressure near the ground surface.

Gouyet (65) observed that atmospheric instability variations were moderate in the regions where he made his measurements. The 50% variation in overall shelter observed for the same type of shelterbelt near Avignon and in the Paris region would therefore result chiefly from mechanical turbulence produced by the depth of the Rhone valley. Seginer (124), in conditions of extreme instability, found a loss of efficiency of less than 30%. Mechanical turbulence, therefore, would be more important than atmospheric instability in reducing the efficiency of shelterbelts. Thus, Fougerouze (62), who found an efficiency zone of over 20% extended only to 11 H, was not sure whether this was attributable to topography or to the tropical climate.

It should be noted at this point that the majority of the studies carried out in temperate zones were conducted on plains, where topography-induced turbulence could not play a major role.
In regions covered by this study, ground relief is not particularly important either, except for the Mediterranean coast of North Africa where plains and mountain ranges alternate. From the aspect of mechanical turbulence, therefore, results obtained in temperate regions should be applicable to the Sahel.

Atmospheric instability is assumed to be confined mainly to zones with broad variations in daily temperature, i.e., to zones bordering the Sahara. This general outline, however, is modified by global phenomena of atmospheric disturbance.

North African coastal winds, which blow from the sea onto a heated continent, probably have have thermal instability, as do the southwesterlies that bring rain to the Sahel and the Sahel-Sudan zones. On the other hand, the Harmattan, the northeast wind of the dry season, is probably more stable. It may be supposed that when the Harmattan comes to an irrigated area where air masses near the ground are cooled by plant evapotranspiration, inversion takes place with resulting atmospheric stability.

Generally speaking, it may be concluded that the overall shelter values for temperate regions can be transposed to African drylands, with the exception of the mountainous Mediterranean coast.

2. Effect on Temperature

In the Mediterranean Climate

Several studies are available on the effect of shelterbelts on temperature in the Mediterranean climate. Thus, during the month of April, Bhalou (17) measured a temperature increase of 0.5°C in the lee of fairly compact Cupressus sempervirens shelterbelts near Oran in Algeria. Table 5 shows more detailed measurements, obtained in Sousse in Tunisia, and Table 6 shows the effect of shelterbelts 5 m high, 6-9 m wide, and composed of five to seven rows of trees in southern Yugoslavia.

Table 5. Shelterbelt-induced increases in winter temperature on the Tunisian coast (47).

<table>
<thead>
<tr>
<th>Type of shelter</th>
<th>Daytime mean temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open zone (control)</td>
<td>11.0</td>
</tr>
<tr>
<td>Permeable plastic shelter</td>
<td>11.5</td>
</tr>
<tr>
<td>Compact reed shelter</td>
<td>12.0</td>
</tr>
</tbody>
</table>

Table 6. Thermal conditions in the lee of the shelterbelts in cold and hot winds in southern Yugoslavia (100).

<table>
<thead>
<tr>
<th>Type of wind</th>
<th>Control</th>
<th>Distance from shelterbelt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 H</td>
</tr>
<tr>
<td>Northwest cold wind</td>
<td>24.4</td>
<td>25.4</td>
</tr>
<tr>
<td>Diff. from control</td>
<td>-</td>
<td>1.0</td>
</tr>
<tr>
<td>Southwest hot wind</td>
<td>30.0</td>
<td>29.2</td>
</tr>
<tr>
<td>Diff. from control</td>
<td>-</td>
<td>-0.8</td>
</tr>
</tbody>
</table>
Shelterbelts increase daytime temperatures when winds are cold, and decrease them when winds are hot (Table 6). This is not surprising, but is of prime importance for understanding the harmful or beneficial effects of shelterbelts in African drylands. Thus, Guyot (63) states that, in the dry North African climate, increase in air temperature in the lee of a shelterbelt may be 5-10°C, and may shrivel or burn crops. Charfi (32) found that temperature can be 4°C higher behind a shelterbelt and that a temperature increase can still be felt at 10-15 H.

In Tropical Climates

Fougerouze (52) has observed the same phenomenon of increased temperature behind a shelterbelt in the trade-wind climate of the West Indies: "Daytime temperatures are consistently higher in sheltered areas. At a distance 4 H from the shelterbelt, temperature increases range between 10° and 30°, depending on radiation and wind velocity. On bare or sparsely covered ground, at the early stage of crops, the average variation is slightly above 20° regardless of the season. On ground covered with vegetation, it is only 1.4°. One might think that this reduction in variation is directly related to actual evapotranspiration, which can be higher in a sheltered zone where the foliage index of crops is generally higher than in an open zone.''

Musnad (95), however, observed a much-reduced effect in Dongola in the northern Sudan (Table 7) in a desert climate. The shelterbelt was the last in a system of eight, which comprised five rows of 10-m high Eucalyptus camaldulensis, oriented at 90° to the prevailing north winds.

Table 7. Average monthly temperature minima and maxima for 1978 at the 1.5-m level, taken in an open zone at 5 H downwind from a fairly compact 12-m high shelterbelt (95).  

<table>
<thead>
<tr>
<th>Month</th>
<th>Wind velocitya (m/sec)</th>
<th>Average minima (°C)</th>
<th>Average minima (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Open zone</td>
<td>Sheltered zone</td>
</tr>
<tr>
<td>Jan.</td>
<td>3.9</td>
<td>5.4</td>
<td>5.8</td>
</tr>
<tr>
<td>Feb.</td>
<td>4.2</td>
<td>9.1</td>
<td>9.5</td>
</tr>
<tr>
<td>Mar.</td>
<td>4.4</td>
<td>11.4</td>
<td>12.0</td>
</tr>
<tr>
<td>Apr.</td>
<td>4.4</td>
<td>19.8</td>
<td>20.0</td>
</tr>
<tr>
<td>May</td>
<td>4.4</td>
<td>21.9</td>
<td>22.4</td>
</tr>
<tr>
<td>June</td>
<td>4.2</td>
<td>22.5</td>
<td>23.2</td>
</tr>
<tr>
<td>July</td>
<td>3.9</td>
<td>25.3</td>
<td>25.4</td>
</tr>
<tr>
<td>Aug.</td>
<td>3.6</td>
<td>22.2</td>
<td>22.4</td>
</tr>
<tr>
<td>Sept.</td>
<td>3.9</td>
<td>24.8</td>
<td>25.0</td>
</tr>
<tr>
<td>Oct.</td>
<td>3.9</td>
<td>21.0</td>
<td>21.5</td>
</tr>
<tr>
<td>Nov.</td>
<td>3.1</td>
<td>9.9</td>
<td>10.6</td>
</tr>
<tr>
<td>Dec.</td>
<td>3.9</td>
<td>8.5</td>
<td>9.1</td>
</tr>
</tbody>
</table>

aWind velocities from Griffiths (58).
Summary

One thing is certain: shelterbelts have a beneficial effect in temperate zones. They increase daytime temperatures in winter and in spring, even though they lower night temperatures thus increasing the risk of early frost. They improve evapotranspiration conditions in the hot season, although this is partly offset by an increase in daytime temperatures. Their usefulness is no longer in doubt.

In the Mediterranean and tropical zones, however, a new factor intervenes: the danger of lethal heat.

In a Mediterranean climate where rains occur in winter, the vegetative period of most crops is balanced between too cold a winter and too hot a summer. Thus, any increase in winter temperatures has very beneficial effects because it extends the vegetation period by permitting an earlier start for the crops. However, in the dry summer season the African Mediterranean zone, hot dry winds blow frequently. These very dry winds come from the desert. They blow from east to west in Morocco, the Chergui; from south to north in Algeria, the Sirocco; and from south-west to north-east in Egypt, the Khamsin. These winds blow 4–5 days/month in summer (the humid season), and slightly more often in May–June. When the winds blow, shelterbelts have a beneficial effect, not only because they reduce evapotranspiration - both temperature and wind velocity are reduced - but also because they protect young shoots and flowers against extreme desiccation that is liable to cause irreversible wilting. On isolated trees, it is not unusual to note fewer fruit on the side exposed to these winds. Thus, Simon and Delecolle (132) have found in Argentina that shelterbelts protected orchards of plum trees from defoliation.

In Africa south of the Sahara, however, the beneficial effect of shelterbelts is more questionable. Because daytime temperatures are already very high, their increase is no longer an advantage for rainfed crops cultivated during the wet season when the rains are brought by cool south-westerly winds in southern Sudan. High temperatures may even kill crops at some stages of their development.

However, it is difficult to foresee the thermal effect of shelterbelts on irrigated crops, either in the wet season or when the Harmattan blows. A temperature increase caused by a drop in wind velocity, entailing a decrease in energy consumed in evapotranspiration, should be expected. However, this drop in wind velocity will also reduce the mixing of cooled air masses at plant level.

At the moment, because of insufficient experimental data, it is impossible to conclude definitely whether the effect of shelterbelts on crops in irrigated areas of the Sahel is positive or negative. Nevertheless, studies carried out in certain other areas allow formulation of certain hypotheses.

Thus, in Nebraska, Brown and Rosenberg (28) recorded temperatures above an irrigated field of sugar beet, where the shelterbelt consisted of two 2–3 m high rows of corn with 20% permeability at a height of 1 m and of 60% at 2 m. The efficiency at 1 m was 40%. The resulting wind decrease caused an average increase of 1.8°C in temperature during the day in the lee of the wind break. Temperature was measured at 25 cm above the crop under conditions of cold advection. During the hottest hours at midday, a thermal inversion took place above the irrigated crop, and developed first in the sheltered zone (Table 8).
To interpret the thermal profiles, it must be considered that, after midday, wind velocity in the open was very low. Thus, air cooled by transpiration stagnated above the plants both in the open and sheltered zones and produced inverted thermal profiles. Temperature differences between open and sheltered zones, moreover, were greater at 1 m above the plants than at 25 cm. These findings support the hypothesis that in irrigated areas, cooling caused by evapotranspiration might reduce the temperature increases created by shelterbelts.

Closer to the area of interest of this publication, Rijks (121) studied the thermal profiles over a newly irrigated cotton field for 1 day in the cool season in Gezira in the Sudan. In the open area, temperatures measured at 2 m varied between 20 and 30°C and wind speed was 3 m/sec. Behind the shelterbelt, from 0.25 to 1.65 m above the crop, there was very little thermal variation, about 0.5°C. From inversion profiles at sunrise, profiles changed to become superadiabatic at 10 am, that is, the temperature at soil level was higher than the adiabatic gradients of 0.6°C/100 m in humid air or of 0.9°C/100 m in dry air. The profiles then started to divide into two: one inversion profile below 1.25 m, which extended into the cotton which was then 75 cm high; and one superadiabatic profile above 1.25 m. At about sundown, a continuous inversion profile was reestablished. Here again, cooling caused by evapotranspiration dominated for irrigated areas.

Finally, Davenport and Hudson (39) studied microclimatic conditions, in the dry season, on fallow lands lying downwind from irrigated cotton fields in the Gezira basin.

**Table 8.** Thermal profiles above an irrigated field of sugar beet in an open zone and a zone protected by a shelterbelt (28).

<table>
<thead>
<tr>
<th>Hour of day</th>
<th>Wind velocity in open zone (m/sec)</th>
<th>Height above crop (cm)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1000</td>
<td>2.2</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>difference</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1100</td>
<td>2.0</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>difference</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1200</td>
<td>1.6</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>difference</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1300</td>
<td>1.0</td>
<td>100</td>
</tr>
<tr>
<td></td>
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<td>25</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>difference</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td>1.0</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>difference</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1600</td>
<td>0.3</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>difference</td>
<td></td>
</tr>
</tbody>
</table>
These authors also observed in inversion of thermal profiles, starting at 11 am, over irrigated crops, whereas above the nonirrigated fallow land the thermal profile remained superadiabatic for the whole day. Average wind velocity and the average daytime temperatures were reduced from 3.3 m/sec to 2.5 m/sec and from 25.5°C to 24.4°C after traveling 300 m over the irrigated fields. The cotton was 60 cm high and measurements were made at a 2-m height.

In conclusion, the midday inversion of the thermal profile above irrigated crops under reduced wind velocity conditions is the most characteristic feature of these studies of microclimate. This phenomenon, in the case of irrigated crops, tempers the harmful temperature rise in the lee of shelterbelts.

3. Effect on Evapotranspiration

Some authors (129, 145) claim that shelterbelts could play an important role in dry climates, mainly because of their significant effect on water conservation. Guyot (63), however, believes that establishment of shelterbelts in arid areas should be considered only in association with irrigation.

In practice, the arid and semi-arid zones of Africa, both north and south of the Sahara, are characterised by a year divided between a rainy season, and a much longer dry season. During the rainy season, the degree to which precipitation is useful to plants depends on its often erratic distribution, and a good distribution relegates shelterbelts to a secondary role. During the dry season, shelterbelts are even less useful, because there is no water to conserve.

Measurements of shelterbelt influence on PET are therefore only of limited value as indicators.

In the Mediterranean Climate

A study by Yakobi and Zohar (141) has shown that, in the arid conditions of the Negev desert, a cypress shelterbelt 6-7 m high reduced evaporation, as measured at 2 m, by 20%. However, most experiments indicated increased evapotranspiration.

Thus, in southern Yugoslavia, Nicota (102) found that shelterbelts increased water consumption by wheat by increasing AET. During a wet summer, AET increase by 2.2% up to a distance of 19 H, whereas, during a drier summer, water consumption increased by 7.9%. These apparently contradictory phenomena have also been observed in arid conditions in Kansas and Nebraska. Rosenberg (122) has shown that irrigated beans used ground water more rapidly in the sheltered than in the open plots. The same phenomenon has been observed for dryland soybean crops (133). The explanation might be that, because crops start earlier and develop faster in a sheltered area, they use up more of the ground water reserves. However, in Rosenberg's irrigated conditions, the INRA model gives a more likely explanation for the increased AET in the lee of shelterbelts. Nonetheless, the important factor is not water consumption as such, but rather consumption efficiency, i.e., the weight of kernels produced in proportion to the water used. In Nicota's case, water efficiency was increased by 10% in the sheltered plots.

In Tropical Climates

The studies available all agree that, in tropical zones, shelterbelts reduce PET to a major extent.
The greatest decrease, 44%, has been measured by Fougerouze (52) in the trade-wind climate of the West Indies. Danquette and Niang (38) state that hedges of Azadirachta indica and Prosopis chilensis reduce PET by 32% in central Senegal. In the south of that country, evaporation in a low-lying rice plantation surrounded by large trees was, over 5 years, 40% lower than an open rice plantation in a wide valley exposed to the wind. Davanport and Hudson (39) recorded a 30% decrease in evaporation in irrigated cotton fields in Gezira in the Sudan. They also found that evaporation decreased above nonirrigated fallow lands. Over a 6-km distance exposed to desert winds, the decrease was 20%; over 17 km, it reached 27%. Also in the Sudan, Musnad (95) found that, at 6 H behind an impermeable shelterbelt in the desert climate of Dongola, evaporation was reduced 27% during the 5 coolest months of the year and 19% during the 7 hottest months.

Summary

That shelterbelts reduce PET in tropical and subtropical zones is not surprising. However, these findings must be placed in a broader context.

For example, in the case of rainfed crops in the Mediterranean climate, I believe that shelterbelts save water in humid and subhumid regions, whereas in arid and semi-arid regions the meager water gains do not compensate for the disadvantages of the shelterbelts.

The situation is more complex in the case of rainfed crops in tropical climates, bearing in mind that both cuticular and stomatal transpiration are controlled both by the AET/PET ratio and by temperature. With a given AET/PET ratio, and AET depends increasingly on the cuticular transpiration as temperature increases (25). This means that, even though shelterbelts reduce AET in rainfed crops in tropical zones, the gain is canceled out by reduced water efficiency during the wet season, resulting from the rise in temperature caused by the shelterbelt.

Finally, before concluding that a decrease in PET results in reduced water consumption in the irrigated area, the water used by the shelterbelt itself should be considered. Although no information is available on this subject in dry zones, it would be rash to claim that a shelterbelt saves water, unless PET is reduced by at least 10%. Even then, trees continue to consume water - even when the fields lie fallow.

4. Effect on Wind Erosion

In the Mediterranean Climate

In a humorous vein, Dubief (44) defined a sandstorm as a wind prohibits eating. Sandstorms in the Sahara last for an average of 6 hours. Their northern limit is Djelfla and Bou Saada in Algeria, where about 5 occur each year. In the central Sahara, their annual frequency may be as high as 100. Dubief found that the minimum wind velocity capable of starting a sandstorm depends on the turbulence. The threshold is at 6 m/sec for very turbulent winds and 12 m/sec for winds with little turbulence. Tricart (139) found that, in the oases of Gourara in Algeria, winds blowing at an average velocity of 11.5 m/sec for 24 hours caused tremendous damage to the traditional anti-erosion network of palm frond palisades, called "afrès".

Najah (70) and Ben Salam (17) have described in detail the traditional techniques of combating wind erosion in the Algerian Souf and in southern Tunisia. These techniques, however, aim at deflecting sand around the oases rather than at combating wind erosion. The work is directed by local experts, and the installation of the "afrès" is subject to community regulations.
Still in North Africa, Griffiths (52) provides some detail on storm frequency (winds with velocities of over 17 m/sec). Melilla, Oran, and Sirte experience only one storm per year, whereas Tripoli experiences 23, which explains why the sands of the Sahara are found right at the gates of Tripoli.

Finally, Nakhdjevani (65) found that, in Khouzistan in Iran, wind erosion was an exponential function of wind velocity. In his samples of windborne matter, he detected a surprising quantity of clay and silt. The erosion threshold, measured at 1.5 m, was estimated at 5.6 m/sec.

In Tropical Climates

An analysis of wind velocity frequencies above the saltation threshold is most important for an understanding of wind erosion phenomena. Table 9 summarizes the wind velocity frequencies capable of producing wind erosion at some stations in the Sahel-Sudanese zone.

The risk of erosion is present in every month (Table 9) but is greatest in January and May when plant cover affords least protection. Thus, the Harmattan is the

<table>
<thead>
<tr>
<th>Month</th>
<th>Direction</th>
<th>Frequency (%)</th>
<th>Direction</th>
<th>Frequency (%)</th>
<th>Direction</th>
<th>Frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan.</td>
<td>ENE</td>
<td>4</td>
<td>E</td>
<td>16</td>
<td>N</td>
<td>2</td>
</tr>
<tr>
<td>Feb.</td>
<td>ENE</td>
<td>10</td>
<td>E</td>
<td>10</td>
<td>N</td>
<td>2</td>
</tr>
<tr>
<td>Mar.</td>
<td>ENE</td>
<td>9</td>
<td>E</td>
<td>7</td>
<td>N</td>
<td>10</td>
</tr>
<tr>
<td>Apr.</td>
<td>SW</td>
<td>7</td>
<td>var.</td>
<td>5</td>
<td>N</td>
<td>8</td>
</tr>
<tr>
<td>May</td>
<td>SW</td>
<td>10</td>
<td>WSW</td>
<td>4</td>
<td>SW</td>
<td>5</td>
</tr>
<tr>
<td>June</td>
<td>SW</td>
<td>7</td>
<td>WSW</td>
<td>4</td>
<td>SW</td>
<td>4</td>
</tr>
<tr>
<td>July</td>
<td>SW</td>
<td>6</td>
<td>SW</td>
<td>4</td>
<td>SW</td>
<td>4</td>
</tr>
<tr>
<td>Aug.</td>
<td>SW</td>
<td>4</td>
<td>SW</td>
<td>2</td>
<td>SW</td>
<td>1</td>
</tr>
<tr>
<td>Sept.</td>
<td>SSW</td>
<td>2</td>
<td>SSW</td>
<td>1</td>
<td>SW</td>
<td>1</td>
</tr>
<tr>
<td>Oct.</td>
<td>SW</td>
<td>0</td>
<td>W</td>
<td>1</td>
<td>N</td>
<td>2</td>
</tr>
<tr>
<td>Nov.</td>
<td>NE</td>
<td>4</td>
<td>E</td>
<td>10</td>
<td>N</td>
<td>2</td>
</tr>
<tr>
<td>Dec.</td>
<td>ENE</td>
<td>3</td>
<td>E</td>
<td>7</td>
<td>N</td>
<td>1</td>
</tr>
</tbody>
</table>

*Wind directions from Griffiths; those for Dori taken at Niamey.*
principal agent of wind erosion. This agrees with studies (89) that determined that wind trajectories in the Sahel zone are from east to west.

Very high winds are infrequent, Maroua was the only location where velocities above 15 m/sec were registered (1% of the time in May). In fact, the incidence of storms varies widely from one location to another. Griffiths (58) notes nine storms from June to September in Kano and only two in Sokoto (he defines a storm as winds with velocities above 17 m/sec). Table 9 also shows that the prevailing wind direction in the dry season is directly opposite to that in the wet season. Thus shelterbelts established at 90° to these directions will both protect crops during the wet season, and control wind erosion during the dry season.

Several studies stress the favorable effect of shelterbelts on wind erosion in tropical regions. Barbier (13) stresses the importance of shelterbelts to control wind erosion in irrigated areas and so minimize sanding up of irrigation canals. Similarly, shelterbelts 60 m wide composed of Eucalyptus microtheca, Prosopis chilensis, or Acacia mellifera have proved to be most effective in protecting irrigated areas in Gezira, in the Sudan from desert sand encroachment (15).

Mapping of Andropogon gayanus hedges in the Maradi region has shown their orientation to be principally north-south. Location is mainly governed by the areas under cultivation, and the spacing usually varies from 50 to 100 m (88). It has been observed that farmers in the Kano region use Pennisetum bajroulis as well as Andropogon gayanus and even standing sorghum straw as antierosion barriers. Planted hegés of Euphorbia balsamifera provide good protection against wind erosion in the Sudan (III).

According to the soil map of Africa (3), it is estimated that one-third of the soils in the Sahel and Sudan are, potentially, highly vulnerable to wind erosion.

Summary

Wind erosion mechanisms shown to apply in temperate zones can be extrapolated directly to the climates and drylands of Africa where several factors contribute to intensify erosion.

Thus, sand from sand-dune formations erodes agricultural lands by abrasion. Clay remains in suspension, once projected into the air by the impact of sand grains. In this way, agricultural land is impoverished as a result of the blanket of sand or by being covered by sand dunes.

The rainfall conditions, characterized by long periods of scant precipitation, also contribute to reduction of soil protection by vegetation. When combined with over-grazing and the extension of annual crops over the past decades, wind erosion progresses at an accelerated pace.

Finally, the more-marked instability of the lower layers of the atmosphere also accentuates wind erosion. The higher wind velocity at ground level, during superadiabatic conditions, increases the power of wind erosion. Furthermore, dust released by abrasion is retained in the air by the upward movement of air masses.

The consequences of wind erosion, notably soil ablation, damage to crops, and accumulation of sand dunes, are spectacular, but the quantities of dust carried in suspension should not be underestimated. In the summer of 1969 alone, 60 million t of dust are estimated to have been carried in this way from the Sahara and the Sahel to the Atlantic Ocean. According to Rapp (118), the loss of fine particles is, in the long run, the most harmful effect of wind erosion in the Sahel. It has even been suggested that the
dust clouds delayed the rains and thus resulted in a distribution of precipitation less favorable to crops because of albedo modification (26).

Given that one-third of the Sahel and Sudan has sandy soil, the control of wind erosion is of major importance for the economic development of this part of Africa.

Shelterbelts have proved effective in combating wind erosion in temperate zones and, in theory, they should also be efficient in African drylands. The biological effects of shelterbelts must, however, be taken into account before considering them on a large scale.

5. Effect on Agricultural Production

In the Mediterranean Climate

Different studies on the effect of shelterbelts on crops in Mediterranean climates are summarized in Table 10.

Table 10. Effect of shelterbelts on agricultural production in the Mediterranean climate

<table>
<thead>
<tr>
<th>Locality</th>
<th>Climatea</th>
<th>Type of shelterbelt</th>
<th>Cropb</th>
<th>Effect of shelterbelt</th>
<th>Protected zone (multiples of HC)</th>
<th>Difference in crop yield (% of control)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereal crops</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Argentina</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>La Plata (144)</td>
<td>SH</td>
<td>Plastic, 50% permeable</td>
<td>Corn grain (R)</td>
<td>0-22</td>
<td>ca. 125</td>
<td></td>
</tr>
<tr>
<td>Bulgaria (108)</td>
<td>SH</td>
<td>-</td>
<td>Wheat (R)</td>
<td>0-20</td>
<td>ca. 123</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Corn (R)</td>
<td>0-20</td>
<td>ca. 117</td>
<td></td>
</tr>
<tr>
<td>Egypt</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alexandria (49)</td>
<td>A</td>
<td>Casuarina sp.</td>
<td>Wheat (I)</td>
<td>0-6</td>
<td>102d</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>straw grain</td>
<td>0-6</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Corn (I) straw</td>
<td>0-6</td>
<td>97</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>kernels</td>
<td>0-6</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>Yugoslavia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skopje (99)</td>
<td>SA</td>
<td>Fairly compact deciduous</td>
<td>Wheat (R) dry summer</td>
<td>0-19</td>
<td>115</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
Table 10 continued.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Climate Type of shelterbelt</th>
<th>Effect of shelterbelt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Protected zone</td>
</tr>
<tr>
<td>Forage crops</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hufuf (142)</td>
<td>D Palm frond palisade</td>
<td>Barley (I) 0-20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oats (I) 0-20</td>
</tr>
<tr>
<td>Egypt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alexandria (49)</td>
<td>A Casuarina sp., permeable</td>
<td>Trifolium alexandrium (I) 1967 0-6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Italy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milan, Turin (30) SH</td>
<td>Populus sp.</td>
<td>Pasture, N side 0-1.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pasture, S side 0-1.25</td>
</tr>
<tr>
<td>Market-garden crops</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Egypt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alexandria (49)</td>
<td>A Casuarina sp.</td>
<td>Artichokes (I) 0-5</td>
</tr>
<tr>
<td>Israel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eilat (73)</td>
<td>D Artificial barrier</td>
<td>Eggplants 0-20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Onions 0-12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pennisetum purpureum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tomatoes 0-10</td>
</tr>
<tr>
<td>Mivtachim (73)</td>
<td>A Artificial barrier</td>
<td>Peanuts (I) 0-20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tomatoes (I) 0-12</td>
</tr>
<tr>
<td>Nir Yizhaq (73)</td>
<td>A Artificial barrier</td>
<td>Garlic (I) 0-20</td>
</tr>
<tr>
<td>Tunisia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chott Meriem (32) A</td>
<td>Palisade of Arundo donax</td>
<td>Potatoes (I) 0-10</td>
</tr>
<tr>
<td>Side Fredj (32)</td>
<td>SA Palisade of Arundo donax</td>
<td>Beans (R) 0-15</td>
</tr>
<tr>
<td>Sousse (47)</td>
<td>SA Plastic 50% perforation</td>
<td>Tomatoes (R) 0-7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Palisade of Arundo donax</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tomatoes (R) 0-1</td>
</tr>
<tr>
<td>Locality</td>
<td>Climate</td>
<td>Type of shelterbelt</td>
</tr>
<tr>
<td>--------------------</td>
<td>---------</td>
<td>---------------------</td>
</tr>
<tr>
<td>Argentina</td>
<td></td>
<td></td>
</tr>
<tr>
<td>San Rafael (132)</td>
<td>A</td>
<td>Populus sp.</td>
</tr>
<tr>
<td>California</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fontana (91)</td>
<td>SA</td>
<td>Eucalyptus globulus</td>
</tr>
<tr>
<td>Orange County (91)</td>
<td>SA</td>
<td>Eucalyptus globulus</td>
</tr>
<tr>
<td>Egypt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thakrit (49)</td>
<td>D</td>
<td>Casuarina sp.</td>
</tr>
<tr>
<td>Israel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nîr Yizhaq (73)</td>
<td>A</td>
<td>Cupressus sempervirens</td>
</tr>
<tr>
<td>Tunisia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tunis (9)</td>
<td>SA</td>
<td>Cupressus sempervirens</td>
</tr>
</tbody>
</table>

---

a) Index of climatic symbols and precipitation: D, desert (<150 mm); A arid (150-300 mm); SA, semi-arid (300-600 mm); SH, subhumid (600-900 mm); and H, humid (>900 mm).
b) Irrigated (I) and rainfed (R).
c) Measurement is in the zone where the effect was observed, not the theoretical extension of the effect.
d) There is no control as such in the open zone. Average yield beyond distances greater than 6 H is used as the control yield.
It is clear that shelterbelts have a beneficial influence on agricultural production in the Mediterranean climate.

However, in the case of cereal cultivation, the data is not conclusive. There is no true summer drought either in Yugoslavia or Bulgaria; and, in Egypt, it is apparent that no positive shelterbelt effects are derived by wheat and corn in irrigated areas. For forage crops, the data are insufficient to allow conclusions to be drawn.

On the other hand, 11 different tests with different market-garden species all show yield increases ranging from 10 to 100%. El Amami and Laberche (47) attribute the better yield of sheltered, nonirrigated tomatoes to an increase in winter temperatures (see Table 4).

The beneficial effect of shelterbelts for citrus fruit is undeniable, because nearly all windfall results from gusts of wind (136). Metcalf (91) suggests two wind velocity thresholds, capable of causing windfall of oranges: 11-14 m/sec, windfall of some fruit; and 14-18 m/sec, total windfall.

According to Griffiths (58), the North African coast suffers storms with winds in excess of 17 m/sec several times each year. It is therefore not surprising that shelterbelts increase the profit of citrus fruit plantations by 70%. Their effectiveness, however, depends on their structure. Near Tunis, a windfall of 25% of the total fruit production has been recorded in a zone 0-3 H in the lee of a compact Cupressus sempervirens var. pyramidalis shelterbelt (136).

No experiments have been undertaken on the effect of shelterbelts on animal husbandry in Mediterranean climates. If shelterbelts have no beneficial effect on this aspect of agriculture, the fact remains that, during summer heat, herds are drawn to their shade, and this can certainly be considered an advantage.

In Tropical Climates

In general, yields of market-garden crops were increased to 4 H in the lee of plastic windbreaks in the trade-wind climate of the West Indies (Table 11). However, beans and tomatoes did not yield as well as with no protection.

Even though the yield in plant matter was increased threefold in the protected areas, in Yambawa, north of Kano in Nigeria, the influence of shelterbelts seemed to be harmful on nonirrigated crops of Vigna unguiculata, which, in the sheltered areas, yielded only 35% of the pods produced in open zones. The shelterbelts in question were compact 10-m high Eucalyptus camaldulensis (Cathrine provenance).

Figure 11 shows the extent of the failure zones of mouscowari sorghum near a Cassia siamea shelterbelt in the Maroua region of the northern Cameroons. It is apparent that the extent of the failure zone is up to 30 m downwind from the undamaged parts of the shelterbelt, i.e., about 4 H. It is interesting to note that a 16-year-old student who happened to be passing by, without being questioned directly, attributed failure to the heat accumulated behind the shelterbelt. It was not possible to observe the prevailing orientation of the damaged crops located along these shelterbelts, which were planted in 1960 (61). It should be added that no damage to plants located under an isolated Cassia siamea was observed, and this is of importance to the overall conclusions of this work.
Table 11. Shelterbelt effect on agricultural production in tropical trade-wind climate in the West Indies with plastic shelterbelts (52).

<table>
<thead>
<tr>
<th>Location</th>
<th>Precipitation (mm)</th>
<th>Windbreak porosity (%)</th>
<th>Crop\textsuperscript{a}</th>
<th>Distance (% of control)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duclos</td>
<td>3160</td>
<td>50</td>
<td>Beans (I)</td>
<td>128</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cucumber (I)</td>
<td>197</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sweet potatoes</td>
<td>121</td>
</tr>
<tr>
<td></td>
<td></td>
<td>65</td>
<td>Sweet potatoes (I)</td>
<td>107</td>
</tr>
<tr>
<td>Saint François</td>
<td>1750</td>
<td>50</td>
<td>Beans</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tomatoes</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Melon (I)</td>
<td>263</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Irrigated (I)

Fig. 11: Distribution of areas of failed sorghum downwind of a shelterbelt of *Cassia siamea* at Tchatibali in the Maroua region of the Cameroons (sketched by Axel Martin Jensen, December 1979).
It has not been possible to study the effect of shelterbelts on crops in the Gezira, where shelterbelts as such do not exist. However, it has been observed that, on the south side of a cotton field surrounded by a 4-m high hedge of Acacia mellifera, blossom was already over and plants bore fruit in a zone 30 m wide, but beyond that point, the cotton plants were still in bloom and in the process of growing, as in unprotected fields.

During dry years, as in 1977 and 1979, scattered damage to millet and peanut crops located at 15-20 m both sides of lines of Azadirachta indica has been noted at Barbey in Senegal (38).

At Bellary in India (precipitation, 508 mm), rainfed crops of sorghum suffered total failure near compact 6-7 m high shelterbelts of Prosopis juliflora, up to a distance of 3 H. Growth returned to normal only at a distance of 6 H. Sorghum growth near these shelterbelts was actually improved after a 60-cm ditch was dug beside them (114).

Because of the lack of data, it is difficult to draw conclusions about the biological effects of shelterbelts in tropical zones. Moreover, Fougerouze's study (52) was carried out in the unusual conditions of cool trade winds (maximum temperature, 32°C) blowing from the sea at a high velocity, average 4.7 m/sec at Duclos and 6.4 m/sec in Saint François. The only studies available indicate that increased production can be expected in conjunction with irrigation and that the risk of damage is present with rainfed crops.

Summary

Given that most shelterbelt networks in tropical zones have been established to protect rainfed crops, damage to these crops deserves further study.

Most authors attribute this damage to root competition for water, which becomes harmful with extended drought. Two tests, where lateral root extension was checked by digging a ditch along the shelterbelt, confirm this hypothesis because the yields of adjacent crops were improved (49, 114).

No damage to crops, however, is found around isolated trees. Indeed the reverse is true with certain species: the most spectacular examples are Acacia albida (54) and Prosopis cineraria (57), both of which have taproot systems. Even with the shallow-rooted species, such as Parkia biglobosa and Butyrospermum parkii, crops do not appear to suffer from competition with trees. Obviously, the roots of an isolated tree cover a wider area than those of trees in shelterbelts, which can develop only in the direction of the cultivated fields. Nonetheless, Fougerouze (52) has also observed yield losses in the lee of plastic shelters, which can in no way be attributed to root competition. Other factors must therefore be involved.

Both Fougerouze and the student from Tchatibali attribute the drop in yield to the temperature increase caused by the shelterbelts. It is in fact possible that shelterbelts increase temperature during the wet season. Moreover, a considerable rise within 5 H can be expected in the lee of compact shelterbelts (see Fig. 7).

All plants do not react in the same manner to temperature increases. Thus, for tomatoes, the rate of photosynthesis is highest between 20°C and 35°C, and it drops sharply at 45°C. Respiration increases exponentially, and ceases to be apparent also at about 45°C. It is for this reason that optimal net assimilation occurs in a narrower and lower temperature range (Fig. 12).
Not all plants have an optimum level as low as 20-25°C. There is, in fact, considerable variation depending, among other things, on the photosynthetic process, which may involve direct CO₂ fixation as for C₃ plants; or fixation requiring preliminary stages as in C₄ plans (23) that have a higher temperature optimum. Of the plants cultivated in the tropics, corn, sugar cane, soybean, cotton, and sorghum are of the C₄ type; rice, wheat, barley, rye, yams, and millet are C₃ (82, 98).

![Graph showing photosynthesis, respiration, and net assimilation in tomatoes as a function of temperature.](image)

**Fig. 12:** Photosynthesis, respiration, and net assimilation in tomatoes as a function of temperature (21).

Temperature ranges, however, are favorable or harmful to plants depending on their stage of development. Thus, Monteith (92) describes an experiment in which the growth of young corn was inhibited by temperatures slightly above 35°C at ground level, whereas growth for corn is normally optimal between 31 and 37°C (98).

Lethal temperatures are of even greater importance than the maximum temperatures that allow growth. The temperature of nontranspiring leaves, for example, readily exceeds that of the ambient air by 10-15°C degrees in sunny weather (85). Lethal temperatures & degrees range between 50-60°C, and mortality depends on how long the tissues have been exposed to these high temperatures.
Livestock yields also depend on temperature. Figure 13 illustrates the response of adult animals, and shows that between 25 and 35°C, yield drops to zero not only for cows, but also for pigs and chickens (24). In general, the temperature range tolerated by young animals is very narrow and higher than for adults (20). High-temperature tolerance depends on the species, and goats usually adapt well to the thermal environment (115).

Meteorological and pedoclimatic data for the Ouagadougou and Dori in Upper Volta are used to distinguish between the Sahel and Sudan zones in terms of their productivity as a function of temperature (Table 12).

Given that the temperature of leaves exposed to sunshine can exceed air temperature by 10-15 °C degrees assimilation is nil at midday, not only because of the closure of stomata, but also because of the high temperatures themselves. If temperature were raised still higher by shelterbelts, even more damage would ensue.

![Graph showing livestock yield as a function of temperature](image)

**Fig. 13:** Livestock yield as a function of temperature (24).

Root growth, in relation to temperature, has not been adequately studied, but it would seem that, even with corn, although it is a C4 plant, optimum growth would drop at temperatures above 30°C (92). This means that, in the wet season, which is the vegetative period for dryland crops, a rise in soil temperature would almost certainly inhibit root-system development both in Dori and in Ouagadougou (Table 12).

**Table 12.** Rainfall (mm) and air and ground temperature (°C) at Ouagadougou and Dori in Upper Volta.

<table>
<thead>
<tr>
<th>Month</th>
<th>Precipitation (mm)</th>
<th>Air (at 2 m from ground) Max</th>
<th>Min</th>
<th>Ground surface Max</th>
<th>Min</th>
<th>Soil at 6 am 0.3 m Max</th>
<th>0.6 m Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ouagadougou 897</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan.</td>
<td>0</td>
<td>34.3</td>
<td>16.5</td>
<td>39.1</td>
<td>12.7</td>
<td>26.2</td>
<td>28.3</td>
</tr>
<tr>
<td>Feb.</td>
<td>2</td>
<td>36.7</td>
<td>19.2</td>
<td>42.0</td>
<td>14.0</td>
<td>28.2</td>
<td>29.8</td>
</tr>
<tr>
<td>Mar.</td>
<td>13</td>
<td>38.6</td>
<td>22.9</td>
<td>45.2</td>
<td>19.5</td>
<td>31.8</td>
<td>32.9</td>
</tr>
</tbody>
</table>
Table 12. Concluded

<table>
<thead>
<tr>
<th>Month</th>
<th>Precipitation (mm)</th>
<th>Air (at 2 m from ground)</th>
<th>Ground surface</th>
<th>Soil at 6 am</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Max</td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>Apr.</td>
<td>16</td>
<td>39.1</td>
<td>25.7</td>
<td>46.1</td>
</tr>
<tr>
<td>May</td>
<td>83</td>
<td>37.0</td>
<td>25.7</td>
<td>43.9</td>
</tr>
<tr>
<td>June</td>
<td>122</td>
<td>33.8</td>
<td>23.1</td>
<td>40.3</td>
</tr>
<tr>
<td>July</td>
<td>203</td>
<td>31.6</td>
<td>22.4</td>
<td>38.0</td>
</tr>
<tr>
<td>Aug.</td>
<td>280</td>
<td>30.3</td>
<td>21.5</td>
<td>36.4</td>
</tr>
<tr>
<td>Sept.</td>
<td>144</td>
<td>31.8</td>
<td>21.6</td>
<td>38.1</td>
</tr>
<tr>
<td>Oct.</td>
<td>33</td>
<td>35.7</td>
<td>22.2</td>
<td>42.0</td>
</tr>
<tr>
<td>Nov.</td>
<td>1</td>
<td>36.7</td>
<td>20.3</td>
<td>42.0</td>
</tr>
<tr>
<td>Dec.</td>
<td>0</td>
<td>34.3</td>
<td>17.1</td>
<td>39.0</td>
</tr>
</tbody>
</table>

Doria 584

<table>
<thead>
<tr>
<th>Month</th>
<th>Precipitation (mm)</th>
<th>Air (at 2 m from ground)</th>
<th>Ground surface</th>
<th>Soil at 6 am</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Max</td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>Jan.</td>
<td>0</td>
<td>33.6</td>
<td>13.6</td>
<td>41.2</td>
</tr>
<tr>
<td>Feb.</td>
<td>0</td>
<td>36.5</td>
<td>15.9</td>
<td>44.2</td>
</tr>
<tr>
<td>Mar.</td>
<td>0</td>
<td>39.1</td>
<td>19.8</td>
<td>49.9</td>
</tr>
<tr>
<td>Apr.</td>
<td>7</td>
<td>41.3</td>
<td>23.9</td>
<td>56.4</td>
</tr>
<tr>
<td>May</td>
<td>36</td>
<td>40.8</td>
<td>26.3</td>
<td>56.0</td>
</tr>
<tr>
<td>June</td>
<td>87</td>
<td>37.8</td>
<td>25.0</td>
<td>51.9</td>
</tr>
<tr>
<td>July</td>
<td>138</td>
<td>33.9</td>
<td>23.2</td>
<td>46.0</td>
</tr>
<tr>
<td>Aug.</td>
<td>206</td>
<td>31.9</td>
<td>22.3</td>
<td>43.2</td>
</tr>
<tr>
<td>Sept.</td>
<td>88</td>
<td>34.0</td>
<td>22.6</td>
<td>45.6</td>
</tr>
<tr>
<td>Oct.</td>
<td>21</td>
<td>38.0</td>
<td>22.0</td>
<td>47.7</td>
</tr>
<tr>
<td>Nov.</td>
<td>1</td>
<td>37.7</td>
<td>18.0</td>
<td>45.3</td>
</tr>
<tr>
<td>Dec.</td>
<td>0</td>
<td>33.8</td>
<td>14.2</td>
<td>40.2</td>
</tr>
</tbody>
</table>

Rainfall data are from Niamey.

It is nevertheless improbable that average temperatures explain damage observed near shelterbelts. If this were the case, a gradual yield reduction would be expected with proximity to the shelterbelt. In fact, crops are completely destroyed in a zone 2 m deep. It would seem that higher temperatures cause burning of young plants at the soil line, leading to crop failure. Although for reasons of methodology, the ground surface temperature values shown in Table 12 should be treated with great caution, their high levels, especially at Dori, strengthen the hypothesis that temperature increases created by shelterbelts could be fatal.

Obviously, it is the dry years that present the greatest danger. There are fewer clouds to reduce direct solar radiation and, also, soil humidity is unable to lower the temperature by evaporation.

Thus, in tropical drylands, it is uncertain that the unfavorable effect of shelterbelts arises solely from root competition, which theoretically could be eliminated by selection of appropriate species or by digging ditches. It is likely that damage to dryland crops found near shelterbelts is derived also from a lethal increase in temperature, inherent to shelterbelts in these climatic conditions.
Although adaptations of local breeds could contribute to livestock resistance to high temperatures, it may be concluded from Fig. 13 that an increase in temperature creates more risks than advantages for animal production. Thus, shade effect apart, it seems unlikely that establishment of shelterbelts is favorable to animal husbandry in tropical drylands.

This analysis does not consider a possible increase of agricultural yield at distances greater than 4 H. However, if a 10 H spacing between shelterbelts is needed to make wind erosion control effective, then not much area is left for crops, especially if damage is suffered on either side of each shelterbelt.

Thus, both field results and theoretical deductions lead to a skeptical view of the usefulness of shelterbelts in dryland cultivation in the Sahel and Sudan zones.
Chapter III

SCREEN AFFORESTATION

The term "screen" is a definition of Le Houerou (83), coined for a forest cover scattered over a grazing and agricultural territory, and it is retained here because of the partial similarity of this type of cover to the shelterbelt.

The physical and biological effects of shelterbelts are complex enough, but those of screen plantations are even more so, because the shade factor is combined with the reduction of wind velocity.

Shelterbelts have been the subject of systematic research for 50 years. However, only a limited number of isolated studies have been made of screen afforestations: these are discussed below.

1. Effect on Wind Velocity

No study is available at present on the effects of screen afforestation on wind velocity. Thus the analysis must be by analogy, using weather data obtained in forests and in oases.

Geiger (53) has summarized studies of wind velocities in the forest, as compared to those in open zones. Wind velocity at ground level is estimated to be reduced by half in a regular high-forest stand, and by even more in selectively cut forest (75). The studies of El Amani and Laberche (47) found that wind velocity in an oasis of southern Tunisia was reduced to one-third of that in the open desert.

These figures should not be transposed directly to screen afforestation, where trees are more widely spaced than in forest plantations or in palm groves. Efficiency is likely to be less, but it is nevertheless possible that a significant regional shelter is achieved because of the resulting uneven profile of the terrain.

2. Effect on Temperature

In temperate zones, forests tend to even out extremes of temperature, the highest temperatures being considerably reduced and the lowest increased as compared to those in open zones. The mean temperatures are usually reduced in the forest (53).

In Mediterranean regions, temperature maxima are the same in forests as in the open, whereas mean temperatures are increased because of the lower minima (11). Both at ground level and 1 m below the surface, absolute temperature maxima are much higher in an open zone than under forest cover. Girard and Baldy (56) have found that air temperature maxima are higher in an oasis of the Sahara than outside. This unexpected finding has been confirmed by El Amani and Laberche (48), who therefore concluded that traditional meteorological measurements (air temperature measurements in a shelter 2 m above ground level) are not representative of conditions at the level of vegetation.

The oasis temperature is probably higher because of an albedo differential such that reflected radiation may be only 10% of total radiation for the oasis, and as much as 50% in the desert (14). Inability of the oasis to use up the energy surplus by means of evapotranspiration therefore results in increased air temperature.
Nevertheless, there is no doubt that the thermal environment is more favorable for plants in the oasis. Temperature measurements at plant level require, however, sophisticated instruments. Of the customary measurements, ground temperature is the best indicator for this purpose. Pierre (110) published ground temperature measurements taken near the oasis of Beni Abbès and in the desert (Table 13).

Table 13. Air and soil temperature measurements in the Beni Abbès oasis on 28 April 1950 and in the desert outside it on 25 April 1950 (110).

<table>
<thead>
<tr>
<th>Hour of the day</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Palm grove</td>
</tr>
<tr>
<td></td>
<td>Air</td>
</tr>
<tr>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>15</td>
<td>23</td>
</tr>
<tr>
<td>18</td>
<td>26</td>
</tr>
<tr>
<td>24</td>
<td>20</td>
</tr>
<tr>
<td>Desert</td>
<td>Air</td>
</tr>
<tr>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>9</td>
<td>24</td>
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<tr>
<td>12</td>
<td>29</td>
</tr>
<tr>
<td>15</td>
<td>32</td>
</tr>
<tr>
<td>18</td>
<td>33</td>
</tr>
<tr>
<td>24</td>
<td>20</td>
</tr>
</tbody>
</table>

Measurements taken at 2 m above the surface - air; and 0.5 cm below the surface - soil.

Although temperature measurements were not taken on the same day, their air-ground ratios confirm the sensory impression received on leaving an oasis (palm grove) and entering the desert.

The total radiation energy, less the reflected energy, is used to heat the ground in the desert. Heat is absorbed by the ground by conductivity and transmitted to the air by convection. In a palm grove, little direct radiation reaches the ground, which is heated by horizontal air movement that is limited near the surface. In these conditions, cooling by means of evapotranspiration is the dominant thermal phenomenon.

3. Effect on Evapotranspiration

In temperate zones, evapotranspiration in the herbaceous strata is reduced by forest cover to a small fraction of that in an open zone by reducing wind velocity and average temperature.

In an oasis of the Mediterranean zone, PET may be halved during the summer (56). A similar PET reduction is observed under forest cover as compared to that in a clearing (20). Finally, in the oasis of Gabes, an evaporation reduction of 33% has been measured (47).

For tropical drylands, Giffard (54) did not find any differences in the evaporation rates under Acacia albida and between them. He believes, however, that the measurements should be repeated. Le Houerou (83) gives figures for PET decrease, at the herbaceous level under the trees, of the order of 50-70%.

However, the PET level is only one of several factors of moisture balance under trees, where part of the precipitation is retained by the crowns and another part used by the trees themselves. Only measurement in the soil can determine the amount of water
In the Mediterranean zone, drying in eucalypt plantations was found to be slower where underbrush was left uncut rather than removed (12).

In tropical drylands, Giffard (54) found that, for the whole year, humidity was higher in the first 10 cm under Acacia albida, compared to the areas between the trees. He also found increased humidity in the soil horizon between 10 and 120 cm, and a drying out below 120 cm (55). Furthermore, in the Rajasthan, the humidity level was found to be two to three times higher in the first 15 cm under forest cover than in uncovered ground (2). Gogoi suggests that tree cover helps to conserve soil water during dry periods. Finally, Koné (77) reports soil humidity figures that are twice as high under forest cover than in uncovered ground.

The few studies extant show that, in spite of interception of precipitation and water consumption by trees, moisture is more available to the herbaceous layer under trees than in the open. These findings are surprising and it would no doubt be a mistake to extend them to all tree cover. Nevertheless, ground surface evaporation is a strictly physical phenomenon and is an exponential function of temperature. Thus it is quite conceivable that, at high temperatures, this factor outweighs all others in determining water balance.

4. Effect on Wind Erosion

Wind erosion under screen afforestation apparently has not been studied. However, based on field observation, it appears to be greatly reduced. In theory, shade provided by screen afforestation has the advantage of reduced convection as compared to the lee of a shelterbelt. Nevertheless, in practice, advection is by far the most important form of air movement at wind velocities capable of causing wind erosion.

The effect of tree cover on soil fertility is better known. Humus resulting from leaf fall from the trees has two effects on the soil: one is positive and results from the chemical properties of humus: the other is negative, at any rate in drylands, because of the physical properties of humus. Thus, the role of organic matter deposited on the surface of the ground, and generally considered to be beneficial, is in fact ambiguous.

Lepoutre (84) has shown that accumulation of organic matter on the soil surface prevents regeneration of Cedrus atlantica in Morocco. The humus layer, having a high water-holding capacity, becomes so desiccated during droughts that heavy rain is required for the soil to have enough water available for plants. In a similar manner, the considerable water-holding capacity of fields requires abundant rainfall for water to penetrate deep into the soil.

Mineralization of organic matter occurs more rapidly in tropical drylands, where the rains coincide with the hot season. The harmful effects of organic-matter accumulation on the ground surface thus become unimportant opposite the beneficial effects of humus formation.

Giffard (54, 55) summarizes results of research under Acacia albida in Senegal as follows: the carbon and nitrogen levels are twice as high under the tree cover than in the open. No consistent results have been found for phosphorus; on permanently fallow land, levels are seven times higher than under trees, whereas on cultivated fields, the difference is slight.
In Jodhpur (P = 400 mm), edaphic conditions under Prosopis cineraria, Prosopis juliflora, Acacia senegal, Albizzia lebbeck, and Tecamella undulata have been compared to those in a similar, but treeless, soil (III). Over a whole profile studied (90 cm), more organic matter and more nitrogen was found under trees than in the open, the nitrogen levels being highest under Prosopis cineraria. As for phosphates, only profiles under Prosopis cineraria show a higher total phosphorus content than on bare ground.

5. Effect on Agricultural Production

A denser and better developed herbaceous cover is usually found under isolated trees, both in the Mediterranean zone and in tropical drylands. In tropical drylands, vegetation develops faster when screened at the outset of the rainy season - although this is not true in the Mediterranean zone - and the herbaceous cover remains green 3-4 weeks longer at the start of the dry season (83), as also generally occurs in the Mediterranean zone.

In the present state of our knowledge, it is not possible to say what role is played by shade or by soil fertilization. In zones that are subject to open grazing, a third factor is involved: the manure produced by the livestock that gravitate toward trees at midday. In this case, it is not a fertility input for the whole area, but rather a local displacement. Nevertheless, it would seem that Senegalese figures for agricultural production under a screen of trees are obtained from experimental areas free of open grazing (109).

Research is Senegal shows that millet and peanut production is twice as high under Acacia albida as in an open zone, and that it can be as high as that in fertilized fields that are unprotected. However, these results are subject to reservation, having been obtained during an especially dry year.

In the drylands of India, cultivation takes place under the cover of Prosopis cineraria that, unlike Acacia albida, is in leaf at the same time as the crops. Agricultural production is supposedly higher under the trees (97). Production of Cenchrus ciliaris, cultivated under Prosopis cineraria, falls with distance from the tree (122). Dry-matter production of the natural herbaceous strata is best under Acacia senegal, followed by Prosopis cineraria, followed by Albizzia lebbeck, Tecamoella undulata, and finally Prosopis juliflora. On the other hand, best herbaceous strata are produced under Prosopis cineraria followed by Acacia senegal, Tecamoella undulata, Prosopis juliflora, and finally Albizzia Tebekk (2).

Experiments carried out in the Sahel show that yield of the herbaceous strata is twice as great under trees as in the full sun (101). It would also seem that, in tropical zones, leguminous plants are favored by shade in their competition with the Gramineae (93).

With regard to livestock yield, Fig. 13 shows the beneficial effect of the shade provided by the screen. Even though local breeds seem better adapted to heat, fodder consumption for all breeds is less when the temperature is 40°C (90).

It would seem therefore that, in tropical drylands, screen afforestation - depending on the species - has a favorable effect both on plant and animal yields. Therefore, although shelterbelts can cause losses in rainfed crops in African drylands, it is advisable, at the present stage of our knowledge, to direct efforts to reclaiming eroded areas by the establishment of screen afforestation.
Stress has already been laid on the fact that the Mediterranean climate is characterized by a rainy season that coincides with the coldest months, and a dry season that coincides with the warmest months. The vegetative period is partly in the cold winter and partly in the dry summer. Yield is governed not only by annual rainfall, but also by the length of the period between the end of winter and the last rains.

Shelterbelts extend the vegetative period by increasing winter temperatures. By reducing wind velocity, water should be saved, above all in wind-swept regions such as coasts and plains. Their protective role in preventing windfall of blossoms and fruit is vital. Finally, shelterbelts have an appreciable role in countering the drying effects on the vegetation of the winds of the Sahara.

The effect of shelterbelts on cereal and forage crops in irrigated areas is not clear, probably because their favorable effect on the water balance has not been considered.

In general, the information available consistently demonstrates the utility of shelterbelts in the Mediterranean climate. Nonetheless, profitability of establishing shelterbelts is not only a matter of their effect on agricultural production. It also involves the space occupied, the value of the wood-fibre yield, and lastly the need for soil protection against wind erosion, which, as we have seen, is the principal reason for their establishment in temperate zones.

The climate of the Sahel and Sudan is characterised by rains that coincide with the hottest months and a dry period extending from November to June. Average monthly temperatures show that it is relatively cool in the rainy months, cool rainy days alternating with hot sunny days during this period.

Temperature increases brought about by shelterbelts may become fatal on hot days if sufficient water is not available to lower temperature by evapotranspiration. The matter is critical because it is precisely at the outset of the rainy season, i.e., at germination, the most vulnerable stage of the vegetative cycle, that rains come at longer intervals. Thus the young plants suffer high temperatures, which may reach lethal levels, behind the shelterbelts.

Therefore, the few measurements and observations available for tropical drylands tend to indicate that shelterbelts are detrimental to rainfed crops. On the other hand, the few biological and microclimatic measurements available provide encouraging evidence on the favorable effect of shelterbelts in irrigated areas. However, it must be concluded that for rainfed crop cultivation, other means than shelterbelts must be found for combating wind erosion.

Little information is available on the screen effects in Mediterranean zones. By analogy with natural regeneration of forest species, where the best "take" of regeneration is found in the shadow of ground vegetation, it seems probable that shelterbelts could have as favorable an influence in a Mediterranean zone as in an arid zone (120, 121).

From a biological point of view, symbiosis of agriculture and trees is a feature of the Sahel and Sudan. Depending on species, leaves fertilize the soil, and shade favors crop and animal husbandry. Leaves often provide forage and fruit is part of the human diet.
From a technical viewpoint, scattered trees might impede mechanization of cultivation. This disadvantage, however, could be reduced by using species with taproots and planting them in squares. Two species, Acacia albida and Prosopis africana, meet these essential requirements. Other species, for example Cordyla pinata, Parinari macrophylla, Prosopis africana, Acacia nilotica, Acacia senegal, Ficus gnaphalocarpa, Balanite aegyptiaca, and Butyrospermum parkii fertilize the soil and partially meet the other requirements.

Wind erosion in the Sahel and Sudan can therefore be fought by screen afforestation.

2. Research Priorities

The research strategy proposed here is predicated on the gaps, and hence on the data still needed for a full assessment of shelterbelts. The specialized literature (66, 124) should be consulted on the subject of instrumentation and methodology of measurement.

Two factors seem important in the Sahel and the Sudan: to reduce wind velocity and to provide shade. Thus, experimental data collection will have to provide for the following: shelterbelts, shading, shelterbelts with shading, and open areas.

The initial phase will not require precise quantitative data, but only a qualitative assessment as to whether shade and reduced wind velocity have positive or negative effects on a given crop.

Artificial shelterbelts, i.e., shelter provided by dry reeds or plastic materials, should be used to facilitate comparison and eliminate the effects of root competition.

Because high-stemmed crops, such as millet or sugar cane, present problems for the construction of screens and shelters, the initial tests should be for short-stemmed crops, such as rainfed peanuts and irrigated rice.

Squares of bare ground should be included in each experiment for measurement of soil temperatures free of plant interference.

In irrigated areas, water consumption must be measured in each experiment because the available area is generally limited by availability of water rather than by geographic constraints. In other words, if shelterbelts lead to savings of water, they will also allow for an increased area.

Biological considerations must come before those of microclimate. Because it is very difficult to summarize the effects of shelterbelts on the microclimate, it will be an advantage to have a definite assessment of the biological data.

Given the considerable climatic variations experienced in the Sahel and the Sudan from year to year, observation over several years would be required to obtain significant mean values for these zones.
Definitions

Adiabatic: the atmospheric temperature gradient at ground level is called adiabatic when air temperature declines with elevation by 0.6°C/100 m in a humid atmosphere, and by 0.9°C/100 m in a dry atmosphere.

Advection: horizontal movement of air masses.

Albedo: ratio of reflected to incident energy.

Efficiency: defined as \[1 - \frac{V_r}{V_0}\] and expressed as a percentage (see page 9).

Evapotranspiration:

Potential evapotranspiration (PET): the theoretical loss of water from an area totally covered by vegetation and perfectly supplied with water (see page 15).

Actual evapotranspiration (AET): the volume of water actually evaporated from a given observed area (see page 15).

Regional efficiency: defined as \[1 - \frac{V_r}{V_0}\] expressed as a percentage where \(V_r\) is the wind velocity measured outside the effects of individual shelterbelts and \(V_0\) is the wind velocity measured in an open area without shelterbelts (see page 13).

Reptation: displacement of soil particles along the ground surface (see page 18).

Saltation: displacement of soil particles by bouncing (see page 18).

Shelter:

Overall shelter: curve of efficiency at a height equal to or lesser than 0.4 H as ordinate; and distance in the lee of the shelterbelt in multiples of its height (H) as abscissa.

Regional shelter: regional efficiency curve - see overall shelter and regional efficiency.

Shelter index: number obtained by integrating the total area under the overall shelter curve - see overall shelter.

Superadiabatic: an atmospheric temperature gradient higher than the adiabatic gradient - see adiabatic.
BIBLIOGRAPHY


